Professor Joseph Le Con

with the kind re

of the writer

H. P. Bowdit

Nov. 1896

Vision

by

H. P. Bowditch,

"

extracted

from

W. H. Howell's

American text-book of physiology.

Philadelphia 1896.

letter, long

XI. THE SPECIAL SENSES.

A. Vision.

The Physiology of Vision.—The eye is the organ by means of which certain vibrations of the luminiferous ether are enabled to affect our consciousness, producing the sensation which we call "light." Hence the essential part of an organ of vision is a substance or an apparatus which, on the one hand, is of a nature to be stimulated by waves of light, and, on the other, is so connected with a nerve that its activity causes nerve-impulses to be transmitted to the nerve-centres. Any animal in which a portion of the ectoderm is thus differentiated and connected may be said to possess an eye—*i. e.* an organ through which the animal may consciously or unconsciously react to the existence of light around it.[1] But the human eye, as well as that of all the higher animals, not only informs us of the existence of light, but enables us to form correct ideas of the direction from which the light comes and of the form, color, and distance of the luminous body. To accomplish this result the substance sensitive to light must form a part of a complicated piece of apparatus capable of very varied adjustments. The eye is, in other words, an optical instrument, and its description, like that of all optical instruments, includes a consideration of its mechanical adjustments and of its refracting media.

Mechanical Movements.—The first point to be observed in studying the movements of the eye is that they are essentially those of a ball-and-socket joint, the globe of the eye revolving freely in the socket formed by the capsule of Tenon through a horizontal angle of almost 88° and a vertical angle of about 80°. The centre of rotation of the eye (which is not, however, an absolutely fixed point) does not coincide with the centre of the eyeball, but lies a little behind it. It is rather farther forward in hypermetropic than in myopic eyes. The movements of the eye, especially those in a horizontal direction, are supplemented by the movements of the head upon the shoulders. The combined eye and head movements are in most persons sufficiently extensive to enable the individual, without any movement of the body, to receive upon the lateral portion of the retina the image of an object directly behind his back. The rotation of the eye in the socket is of course easiest and most extensive when the eyeball has an approximately spherical shape, as in the normal or emmetropic eye. When the antero-posterior diameter is very much longer than those

[1] In certain of the lower orders of animals no local differentiations seem to have occurred, and the whole surface of the body appears to be obscurely sensitive to light. See Nagel: *Der Lichtsinn augenloser Thiere*, Jena, 1896.

at right angles to it, as in extremely myopic or short-sighted eyes, the rotation of the eyeball may be considerably limited in its extent. In addition to the movements of rotation round a centre situated in the axis of vision, the eyeball may be moved forward and backward in the socket to the extent of about one millimeter. This movement may be observed whenever the eyelids are widely opened, and is supposed to be effected by the simultaneous contraction of both the oblique muscles. A slight lateral movement has also been described.

The movements of the eye will be best understood when considered as referred to three axes at right angles to each other and passing through the centre of rotation of the eye. The first of these axes, which may be called the longitudinal axis, is best described as coinciding with the axis of vision when, with head erect, we look straight forward to the distant horizon; the second, or transverse, axis is defined as a line passing through the centres of rotation of the two eyes; and the third, or vertical, axis is a vertical line necessarily perpendicular to the other two and also passing through the centre of rotation. When the axis of vision coincides with the longitudinal axis, the eye is said to be in the *primary position.* When it moves from the primary position by revolving around either the transverse or the vertical axis, it is said to assume *secondary positions.* All other positions are called *tertiary* positions, and are reached from the primary position by rotation round an axis which lies in the same plane as the vertical and horizontal axis—*i. e.* in the "equatorial plane" of the eye. When the eye passes from a secondary to a tertiary position, or from one tertiary position to another, the position assumed by the eye is identical with that which it would have had if it had reached it from the primary position by rotation round an axis in the equatorial plane. In other words, every direction of the axis of vision is associated with a fixed position of the whole eye—a condition of the greatest importance for the easy and correct use of the eyes. A rotation of the eye round its antero-posterior axis takes place in connection with certain movements, but authorities differ with regard to the direction and amount of this rotation.

Muscles of the Eye.—The muscles of the eye are six in number—viz: the superior, inferior, internal and external recti, and the superior and inferior oblique. This apparent superfluity of muscles (for four muscles would suffice to turn the eye in any desired direction) is probably of advantage in reducing the amount of muscular exertion required to put the eye into any given position, and thus facilitating the recognition of slight differences of direction, for, according to Fechner's psycho-physic law the smallest perceptible difference in a sensation is proportionate to the total amount of the sensation. Hence if the eye can be brought into a given position by a slight muscular effort, a change from that position will be more easily perceived than if a powerful effort were necessary.

Each of the eye-muscles, acting singly, tends to rotate the eye round an axis which may be called the axis of rotation of that muscle. Now, none of the muscles have axes of rotation lying exactly in the equator of the eye—*i. e.* in a plane passing through the centre of rotation perpendicular to the axis

of vision.[1] But all movements of the eye from the primary position take place, as we have seen, round an axis lying in this plane. Hence all such movements must be produced by more than one muscle, and this circumstance also is probably of advantage in estimating the extent and direction of the movement. In this connection it is interesting to note that the eye-muscles have an exceptionally abundant nerve-supply—a fact which it is natural to associate with their power of extremely delicate adjustment. It has been found by actual count that in the muscles of the human eye each nerve-fibre supplies only two or three muscle-fibres, while in the muscles of the limbs the ratio is as high as 1 to 40–125.[2]

Although each eye has its own supply of muscles and nerves, yet the two eyes are not independent of each other in their movements. The nature of their connections with the nerve-centres is such that only those movements are, as a rule, possible in which both axes of vision remain in the same plane. This condition being fulfilled, the eyes may be together directed to any desired point above, below, or at either side of the observer. The axes may also be converged, as is indeed necessary in looking at near objects, and to facilitate this convergence the internal recti muscles are inserted nearer to the cornea than the other muscles of the eye. Though in the ordinary use of the eyes there is never any occasion to diverge the axes of vision, yet most persons are able to effect a divergence of about four degrees, as shown by their power to overcome the tendency to double vision produced by holding a prism in front of one of the eyes. The nervous mechanism through which this remarkable co-ordination of the muscles of the two eyes is effected, and their motions limited to those which are useful in binocular vision, is not completely understood, but it is supposed to have its seat in part in the tubercula quadrigemina, in connection with the nuclei of origin of the third, fourth, and sixth cranial nerves. Its disturbance by disease, alcoholic intoxication, etc. causes strabismus, confusion, dizziness, and double vision.

A nerve termination sensitive to light, and so arranged that it can be turned in different directions, is sufficient to give information of the direction from which the light comes, for the contraction of the various eye-muscles indicates, through the nerves of muscular sense, the position into which the eye is normally brought in order to best receive the luminous rays, or, in other words, the direction of the luminous body. The eye, however, informs us not only of the direction, but of the form of the object from which the light proceeds; and to understand how this is effected it will be necessary to consider the refracting media of the eye by means of which an optical image of the luminous object is thrown upon the expanded termination of the optic nerve—viz. the retina.

Dioptric Apparatus of the Eye.—For the better comprehension of this portion of the subject a few definitions in elementary optics may be given. A

[1] The axes of rotation of the internal and external recti, however, deviate but slightly from the equatorial plane.

[2] P. Tergast: "Ueber das Verhältniss von Nerven und Muskeln," *Archiv für mikr. Anat.*, ix. 36–46.

dioptric system in its simplest form consists of two adjacent media which have different indices of refraction and whose surface of separation is the segment of a sphere. A line joining the middle of the segment with the centre of the sphere and prolonged in either direction is called the axis of the system. Let the line *A P B* in Figure 213 represent in section such a spherical surface the

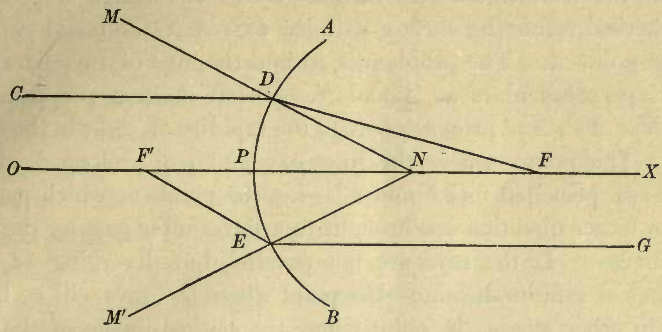


FIG. 213.—Diagram of simple optical system (after Foster).

centre of which is at *N*, the rarer medium being to the left and the denser medium to the right of the line. Any ray of light which, in passing from the rarer to the denser medium, is normal to the spherical surface will be unchanged in its direction—*i. e.* will undergo no refraction. Such rays are represented by the lines *O P*, *M D*, and *M′ E*. If a pencil of rays having its origin in the rarer medium at any point in the axis falls upon the spherical surface, there will be one ray—viz. the one which coincides with the axis of the system, which will pass into the second medium unchanged in its direction. This ray is called the *principal ray* (*O P*), and its point of intersection (*P*) with the spherical surface is called the *principal point*. The centre of the sphere (*N*) through which the principal ray necessarily passes is called the *nodal point*. All the other rays in the pencil are refracted toward the principal ray by an amount

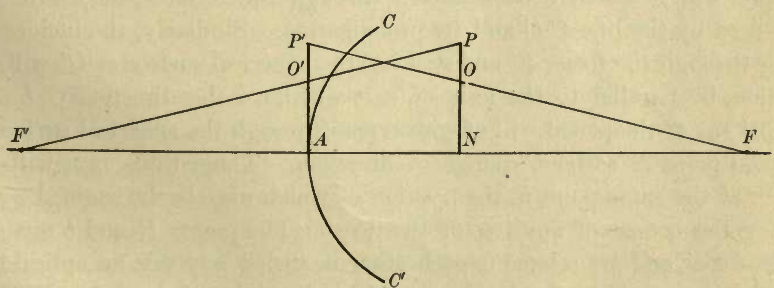


FIG. 214.—Diagram to show method of finding principal foci (Neumann).

which depends, for a given radius of curvature, upon the difference in the refractive power of the media, or, in other words, upon the retardation of light in passing from one medium to the other. If the incident rays have their origin at a point infinitely distant on the axis—*i. e.* if they are parallel to each other—they will all be refracted to a point behind the spherical surface known

as the *principal focus*, F. There is another *principal focus* (F') in front of the spherical surface—viz. the point from which diverging incident rays will be refracted into parallelism on passing the spherical surface, or, in other words, the point at which parallel rays coming from the opposite direction will be brought to a focus. The position of these two principal foci may be determined by the construction shown in Figure 214. Let $C A C'$ represent a section of a spherical refracting surface with the axis $A N$, the nodal point N, and the principal point A. The problem is to find the foci of rays parallel to the axis. Erect perpendiculars at A and N. Set off on each perpendicular distances No, Np, $A o'$, $A p'$ proportionate to the rapidity of light in the two media (*e. g.* 2 : 3). The points where the lines $p' o$ and $p o'$ prolonged will cut the axis are the two principal foci F and F'—*i. e.* the points at which parallel rays coming from either direction are brought to a focus after passing the spherical refracting surface. If the rays are not parallel, but diverging—*i. e.* coming from an object at a finite distance—the point where the rays will be brought to a focus, or, in other words, the point where the optical image of the luminous object will be formed, may be determined by a construction which combines any two of the three rays whose course is given in the manner above described. Thus in Figure 215 let $A N$ be the axis, and F and F' the principal foci of

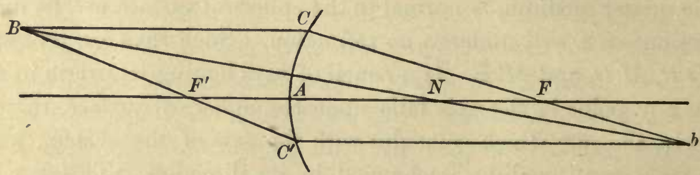


FIG. 215.—Diagram to show method of finding conjugate foci.

the spherical refracting surface $C A C'$, with a nodal point at N. Let B be the origin of a pencil of rays the focus of which is to be determined. Draw the line $B C$ representing the course of an incident ray parallel to the axis. This ray will necessarily be refracted through the focus F, its course being represented by the line $C F$ and its prolongation. Similarly, the incident ray passing through the focus F' and striking the spherical surface at C' will, after refraction, be parallel to the axis—*i. e.* it will have the direction $C' b$. The principal ray of the pencil will of course pass through the spherical surface and the nodal point N without change of direction. These three rays will come together at the same point b, the position of which may be determined by constructing the course of any two of the three. The points B and b are called conjugate foci, and are related to each other in such a way that an optical image is formed at one point of a luminous object situated at the other. When the rays of light pass through several refracting surfaces in succession their course may be determined by separate calculations for each surface, a process which is much simplified when the surfaces are "centred"—*i. e.* have their centres of curvature lying in the same axis, as is approximately the case in the eye.

Refracting Media of the Eye.—Rays of light in passing through the eye penetrate seven different media and are refracted at seven surfaces. The media

are as follows: layer of tears, cornea, aqueous humor, anterior capsule of lens, lens, posterior capsule of lens, vitreous humor. The surfaces are those which separate the successive media from each other and that which separates the tear layer from the air. For purposes of practical calculation the number of surfaces and media may be reduced to three. In the first place, the layer of tears which moistens the surface of the cornea has the same index of refraction as the aqueous humor. Hence the index of refraction of the cornea may be left out of account, since, having practically parallel surfaces and being bounded on both sides by substances having the same index of refraction, it does not influence the direction of rays of light passing through it. For this same reason objects seen obliquely through a window appear in their true direction, the refraction of the rays of light on entering the glass being equal in amount and opposite in direction to that which occurs in leaving it. For purposes of optical calculation we may, therefore, disregard the refraction of the cornea (which, moreover, does not differ materially from that of the aqueous humor), and imagine the aqueous humor extending forward to the anterior surface of the layer of tears which bathes the corneal epithelium. Furthermore, the capsule of the lens has the same index of refraction as the outer layer of the lens itself, and for optical purposes may be regarded as replaced by it. Hence the optical apparatus of the eye may be regarded as consisting of the following three refracting media: Aqueous humor, index of refraction 1.33; lens, average index of refraction 1.45; vitreous humor, index of refraction 1.33. The surfaces at which refraction occurs are also three in number: Anterior surface of cornea, radius of curvature 8 millimeters; anterior surface of lens, radius of curvature 10 millimeters; posterior surface of lens, radius of curvature 6 millimeters. It will thus be seen that the anterior surface of the lens is less and the posterior surface more convex than the cornea.

To the values of the optical constants of the eye as above given may be added the following: Distance from the anterior surface of the cornea to the anterior surface of the lens, 3.6 millimeters; distance from the posterior surface of the lens to the retina, 15. millimeters; thickness of lens, 3.6 millimeters.

The methods usually employed for determining these constants are the following: The indices of refraction of the aqueous and vitreous humor are determined by filling the space between a glass lens and a glass plate with the fresh humor. The aqueous or vitreous humor thus forms a convex or concave lens, from the form and focal distance of which the index can be calculated. Another method consists in placing a thin layer of the medium between the hypothenuse surfaces of two right-angled prisms and determining the angle at which total internal reflection takes place. In the case of the crystalline lens the index is found by determining its focal distance as for an ordinary lens, and solving the equation which expresses the value of the index in terms of radius of curvature and focal distance, thickness, and focal length. The refractive index of the lens increases from the surface toward the centre, a peculiarity which tends to correct the disturbances due to spherical aberration, as well as to increase the refractive power of the lens as a whole.

The curvature of the refracting surfaces of the eye is determined by an instrument known as an ophthalmometer, which measures the size of the reflected image of a known object in the various curved surfaces. The radius of curvature of the surface is determined by the following formula: $B:b = A:\frac{r}{2}$; or $r = \frac{2Ab}{B}$, in which B = the size of the object, b = the size of the image, A = distance between the object and the reflecting surface, and r = the radius of the reflecting surface. The distances between the various surfaces of the eye are measured on frozen sections of the organ, or can be determined upon the living eye by optical methods too complicated to be here described. It should be borne in mind that the above values of the so-called "optical constants" of the eye are subject to considerable individual variation, and that the statements of authors concerning them are not always consistent.

The refracting surfaces of the eye may be regarded as still further simplified, and a so-called "reduced eye" constructed which is very useful for purposes of optical calculation. This reduced eye, which for optical purposes is the equivalent of the actual eye, is regarded as consisting of a single refracting medium having an index of 1.33, a radius of curvature of 5.017 millimeters, its principal point 2.148 millimeters behind the anterior surface of the cornea, and its nodal point 0.04 millimeter in front of the posterior surface of the lens.[1] The principal foci of the reduced eye are respectively 12.918 millimeters in front of and 22.231 millimeters behind the anterior surface of the cornea. Its optical power is equal to 50.8 dioptries.[2] The position of this imaginary refracting surface is indicated by the dotted line in figure 216. The

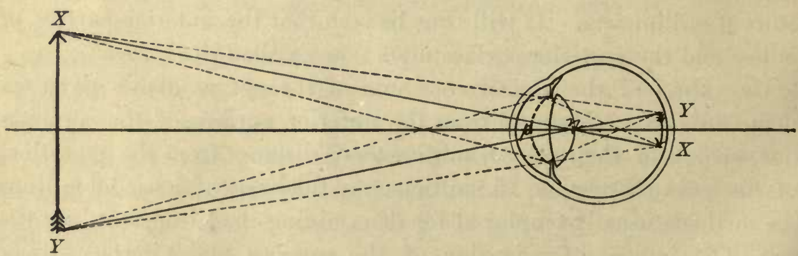


FIG. 216.—Diagram of the formation of a retinal image (after Foster).

nodal point, n, in this construction may be regarded as the crossing-point of all the principal rays which enter the eye, and, as these rays are unchanged in their direction by refraction, it is evident that the image of the point whence they proceed will be formed at the point where they strike the retina. Hence to determine the size and position of the retinal image of any external object—*e. g.* the arrow in Figure 216—it is only necessary to draw lines from various

[1] Strictly speaking, there are in this imaginary refracting apparatus which is regarded as equivalent to the actual eye two principal and two nodal points, each pair about 0.4 millimeter apart. The distance is so small that the two points may, for all ordinary constructions, be regarded as coincident.

[2] The optical power of a lens is the reciprocal of its focal length. The dioptry or unit of optical power is the power of a lens with a focal length of 1 meter.

points of the object through the above-mentioned nodal point and to prolong them till they strike the retina. It is evident that the size of the retinal image will be as much smaller than that of the object as the distance of the nodal point from the retina is smaller than its distance from the object.

According to the figures above given, the nodal point is about 7.2 millimeters behind the anterior surface of the cornea and about 15.0 millimeters in front of the retina. Hence the size of the retinal image of an object of known size and distance can be readily calculated—a problem which has frequently to be solved in the study of physiological optics. The construction given in Figure 216 shows that from all external objects *inverted* images are projected upon the retina, and such inverted images can actually be seen under favorable conditions. If, for instance, the eye of a white rabbit, which contains no choroidal pigment, be excised and held with the cornea directed toward a window or other source of light, an inverted image of the luminous object will be seen through the transparent sclerotic in the same way that one sees an inverted image of a landscape on the ground-glass plate of a photographic camera. The question is often asked, "Why, if the images are inverted in the retina, do we not see objects upside down?" The only answer to such a question is that it is precisely *because* images are inverted on the retina that we do *not* see objects upside down, for the eye has learned through lifelong practice to associate an impression made upon any portion of the retina with light coming from the *opposite* portion of the field of vision. Thus if an image falls upon the lower portion of the retina, our experience, gained chiefly through muscular movements and tactile sensations, has taught us that this image must correspond to an object in the upper portion of our field of vision. In whatever way the retina is stimulated the same effect is produced. If, for instance, gentle pressure is made with the finger on the lateral portion of the eyeball through the closed lids a circle of light known as a phosphene immediately appears on the opposite side of the eye. Another good illustration of the same general rule is found in the effect of throwing a shadow upon the retina from an object as close as possible to the eye. For this purpose place a card

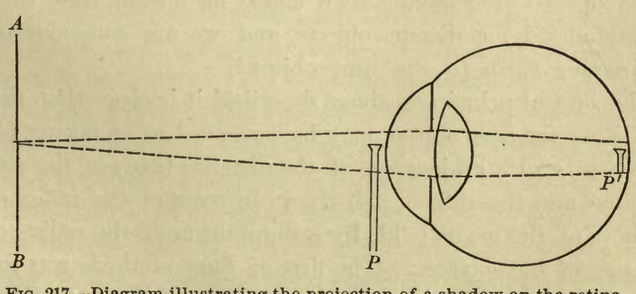


FIG. 217.—Diagram illustrating the projection of a shadow on the retina.

with a small pin-hole in it in front of a source of light, and three or four centimeters distant from the eye. Then hold some object smaller than the pupil—*e. g.* the head of a pin—as close as possible to the cornea. Under these conditions neither the pin-hole nor the pin-head can be really seen—*i. e.* they

are both too near to have their image focussed upon the retina. The pin-hole becomes itself a source of light, and appears as a luminous circle bounded by the shadow thrown by the edge of the iris. Within this circle of light is seen the shadow of the pin-head, but the pin-head appears *inverted*, for the obvious reason that the eye, being accustomed to interpret all retinal impressions as corresponding to objects in the opposite portion of the field of vision, regards the upright shadow of the pin-head as the representation of an inverted object. The course of the rays in this experiment is shown in Figure 217, in which A B represents the card with a pin-hole in it, P the pin, and P' its upright shadow thrown on the retina.

Accommodation.—From what has been said of conjugate foci and their relation to each other it is evident that any change in the distance of the object from the refracting media will involve a corresponding change in the position of the image, or, in other words, only objects at a given distance can be focussed upon a plane which has a fixed position with regard to the refracting surface or surfaces. Hence all optical instruments in which the principle of conjugate foci finds its application have adjustments for distance. In the telescope and opera-glass the adjustment is effected by changes in the distance between the lenses, and in the photographic camera by a change in the position of the ground-glass plate representing the focal plane. In the microscope the adjustment is effected by changing the distance of the object to suit the lenses, the higher powers having a shorter "working distance."

We must now consider in what way the eye adapts itself to see objects distinctly at different distances. That this power of adaptation, or "accommodation," really exists we can easily convince ourselves by looking at different objects through a network of fine wire held near the eyes. When with normal vision the eyes are directed to the distant objects the network nearly disappears, and if we attempt to see the network distinctly the outlines of the distant objects become obscure. In other words, it is impossible to see both the network and the distant objects distinctly at the same time. It is also evident that in accommodation for distant objects the eyes are at rest, for when they are suddenly opened after having been closed for a short time they are found to be accommodated for distant objects, and we are conscious of a distinct effort in directing them to any near object.[1]

From the optical principles above described it is clear that the accommodation of the eye for near objects may be conceived of as taking place in three different ways: 1st, By an increase of the distance between the refracting surfaces of the eye and the retina; 2d, By an increase of the index of refraction of one or more of the media; 3d, By a diminution of the radius of curvature of one or more of the surfaces. The first of these methods was formerly supposed to be the one actually in use, a lengthening of the eyeball under a pres-

[1] It has been shown by Beer (*Archiv für die gesammte Physiologie*, lviii. 523) that in fishes the eyes when at rest are accommodated for *near* objects, and that accommodation for *distant* objects is effected by the contraction of a muscle for which the name "retractor lentis" is proposed.

sure produced by the eye-muscles being assumed to occur. This lengthening would, in the case of a normal eye accommodating itself for an object at a distance of 15 centimeters, amount to not less than 2 millimeters—a change which could hardly be brought about by the action of any muscles connected with the eye. Moreover, accommodation changes can be observed upon electrical stimulation of the excised eye. Its mechanism must, therefore, lie within the eye itself. As for the second of these methods, there is no conceivable way by which a change in the index of refraction of the media can be effected, and we are thus forced to the conclusion that accommodation is brought about by a change in the curvature of the refracting surfaces—*i. e.* by a method quite different from any which is employed in optical instruments of human construction. Now, by measuring the curvature of the cornea of a person who looks alternately at near and distant objects it has been shown that the cornea undergoes no change of form in the act of accommodation. By a process of exclusion, therefore, the lens is indicated as the essential organ in this function of the eye, and, in fact, the complicated structure and connections of the lens at once suggest the thought that it is in the surfaces of this portion of the eye that the necessary changes take place. Indeed, from a teleological point of view the lens would seem somewhat superfluous if it were not important to have a transparent refracting body of *variable* form in the eye, for the amount of refraction which takes place in the lens could be produced by a slightly increased curvature of the cornea. Now, the changes of curvature which occur in the surfaces of the lens when the eye is directed to distant and near objects alternately can be actually observed and measured with considerable accuracy. For this purpose the changes in the form, size, and position of the images of brilliant objects reflected in these two surfaces are studied. If a candle is held in a dark room on a level with and about 50 centimeters away from the eye in which the accommodation is to be studied, an observer, so placed that his own axis of vision makes about the same angle (15°–20°) with that of the observed eye that is made by a line joining the observed eye and the candle, will readily see a small upright image of the candle reflected in the cornea of the observed eye. Near this and within the outline of the pupil are two other images of the candle, which, though much less easily seen than the corneal image, can usually be made out by a proper adjustment of the light. The first of these is a large faint upright image reflected from the anterior surface of the lens, and the second is a small inverted image reflected from the posterior surface of the lens. It will be observed that the size of these images varies with the radius of curvature of the three reflecting surfaces as given on p. 749. The relative size and position of these images having been recognized while the eye is at rest—*i. e.* is accommodated for distance—let the person who is under observation be now requested to direct his eye to a near object lying in the same direction. When this is done the corneal image and that reflected from the posterior surface of the lens will remain unchanged,[1]

[1] A very slight diminution in size may sometimes be observed in the image reflected from the posterior surface of the lens.

while that reflected from the anterior surface of the lens will become smaller and move toward the corneal image. This change in the size and position of the reflected image can only mean that the surface from which the reflection takes place has become more convex and has moved forward. Coincident with this change a contraction of the pupil will be observed.

An apparatus for making observations of this sort is known as the phakoscope of Helmholtz (Fig. 218). The eye in which the changes due to accommodation are to be observed is placed at an opening in the back of the instrument at *C*, and directed alternately to a needle placed in the opening *D* and to a distant object lying in the same direction. Two prisms at *B* and *B′* serve to throw the light of a candle on to the observed eye, and the eye of an observer at *A* sees the three reflected images, each as two small square spots of light. The movement and the change of size of the image reflected from the anterior surface of the lens can be thus much better observed than when a candle-flame is used.

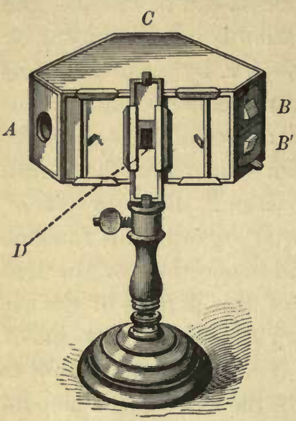


Fig. 218.—Phakoscope of Helmholtz.

The course of the rays of light in this experiment is shown diagrammatically in Figure 219. The observed eye is directed to the point *A*, while the candle and the eye of the observer are placed symmetrically on either side. The images of the candle reflected from the various surfaces of the eye will be seen projected on the dark background of the pupil

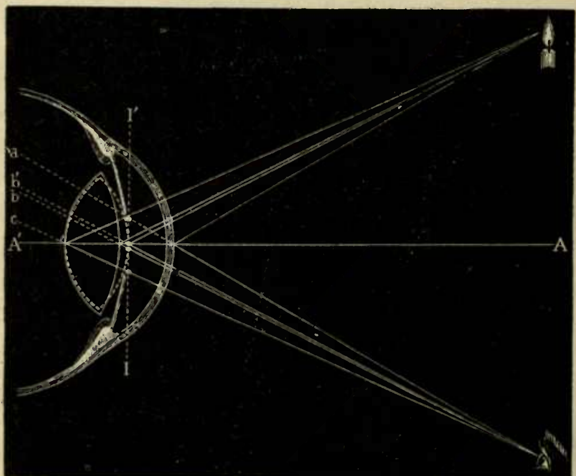


Fig. 219.—Diagram explaining the change in the position of the image reflected from the anterior surface of the crystalline lens (Williams, after Donders).

in the directions indicated by the dotted lines ending at *a*, *b*, and *c*. When the eye is accommodated for a near object the middle one of the three images moves nearer the corneal image—*i. e.* it changes in its direction from *b* to *b′*, showing that the anterior surface of the lens has bulged forward into the position indi-

cated by the dotted line. The change in the appearance of the images is represented diagrammatically in Figure 220. On the left is shown the appearance of the images as seen when the eye is at rest, *a* representing the corneal image, *b* that reflected from the anterior, and *c* that from the posterior surface of the lens when the observing eye and the candle are in the position repre-

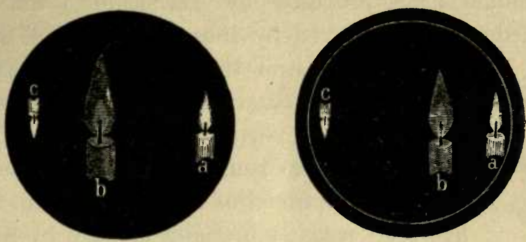


Fig. 220.—Reflected images of a candle-flame as seen in the pupil of an eye at rest and accommodated for near objects (Williams).

sented in Figure 219. The images are represented as they appear in the dark background of the pupil, though of course the corneal image may, in certain positions of the light, appear outside of the pupillary region. When the eye is accommodated for near objects the images appear as shown in the circle on the right, the image *b* becoming smaller and brighter and moving toward the corneal image, while the pupil contracts as indicated by the circle drawn round the images.

The changes produced in the eye by an effort of accommodation are indicated in Figure 221, the left-hand side of the diagram showing the condition

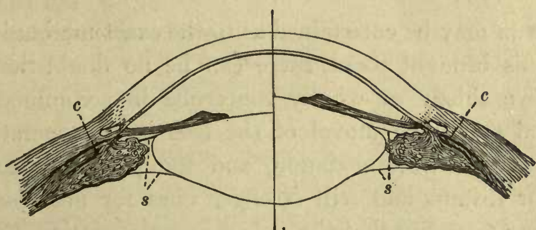


Fig. 221.—Showing changes in the eye produced by the act of accommodation (Helmholtz).

of the eye at rest, and the right-hand side that in extreme accommodation for near objects.

It will be observed that the iris is pushed forward by the bulging lens and that its free border approaches the median line. In other words, the pupil is contracted in accommodation for near objects. The following explanation of the mechanism by which this change in the shape of the lens is effected has been proposed by Helmholtz, and is still generally accepted. The structure of the lens is such that by its own elasticity it tends constantly to assume a more convex form than the pressure of the capsule and the tension of the suspensory ligaments (*s*, *s*, Fig. 221) allow. This pressure and tension are diminished when the eye is accommodated for near vision by the contraction of the ciliary muscles (*c*, *c*, Fig. 221), most of whose fibres, having their origin at the

point of union of the cornea and sclerotic, extend radially outward in every direction and are attached to the front part of the choroid. The contraction of the ciliary muscle, drawing forward the membranes of the eye, will relax the tension of the suspensory ligament and allow the lens to take the form determined by its own elastic structure. According to another theory of accommodation proposed by Tscherning,[1] the suspensory ligament is stretched and not relaxed by the contraction of the ciliary muscle.

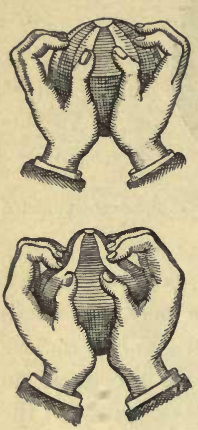


FIG. 222.—To illustrate Schoen's theory of accommodation.

In consequence of the pressure thus produced upon the lens, the soft external portions are moulded upon the harder nuclear portion in such a way as to give to the anterior (and to some extent to the posterior) surface a hyperboloid instead of a spherical form. A similar theory has been recently brought forward by Schoen,[2] who compares the action of the ciliary muscle upon the lens to that of the fingers compressing a rubber ball, as shown in Figure 222. These theories have an advantage over that offered by Helmholtz, inasmuch as they afford an explanation of the presence in the ciliary muscle of circular fibres, which, on the theory of Helmholtz, seem to be superfluous. They also make the fact of so-called "astigmatic accommodation" comprehensible. This term is applied to the power said to be sometimes gradually acquired by persons with astigmatic[3] eyes of correcting this defect of vision by accommodating the eye more strongly in one meridian than another.[4]

Whatever views may be entertained as to the exact mechanism by which its change of shape is brought about, there can be no doubt that the lens is the portion of the eye chiefly or wholly concerned in accommodation, and it is accordingly found that the removal of the lens in the operation for cataract destroys the power of accommodation, and the patient is compelled to use convex lenses for distant and still stronger ones for near objects.

It is interesting to notice that the act of accommodation, though distinctly voluntary, is performed by the agency of the *unstriped* fibres of the ciliary muscles. It is evident, therefore, that the term "involuntary" sometimes applied to muscular fibres of this sort may be misleading. The voluntary character of the act of accommodation is not affected by the circumstance that the will needs, as a rule, to be assisted by visual sensations. The fact that most persons cannot affect the necessary change in the eye unless they direct their attention to some near or far object is only an instance of the close relation between sensory impressions and motor impulses, which is further exem-

[1] *Archives de Physiologie*, 1894, p. 40. [2] *Archiv für die gesammte Phys.*, lix. 427.

[3] See p. 763.

[4] Recent observations by Hess (*Archiv f. Ophthalmologie*, xlii. 288) tend to confirm the Helmholtz theory by showing that the suspensory ligament is relaxed and not stretched in accommodation for near objects.

plified by such phenomena as the paralysis of the lip of a horse caused by the division of the trifacial nerve. It is found, moreover, that by practice the power of accommodating the eye without directing it to near and distant objects can be acquired. The nerve-channels through which accommodation is affected are the anterior part of the nucleus of the third pair of nerves lying in the extreme hind part of the floor of the third ventricle, the most anterior bundle of the nerve-root, the third nerve itself, the lenticular ganglion, and the short ciliary nerves (see diagram p. 769).

The mechanism of accommodation is affected in a remarkable way by drugs, the most important of which are atropia and physostigmin, the former paralyzing and the latter stimulating the ciliary muscle. As these drugs exert a corresponding effect upon the iris, it will be convenient to discuss their action in connection with the physiology of that organ.

The changes occurring in the eye during the act of accommodation are indicated in the following table, which shows, both for the actual and the reduced eye, the extent to which the refracting media change their form and position, and the consequent changes in the position of the foci :

	Accommodation for			
Actual Eye.	distant objects.		near objects.	
Radius of cornea	8	mm.	8	mm.
Radius of anterior surface of lens	10	"	6	"
Radius of posterior surface of lens	6	"	5.5	"
Distance from cornea to anterior surface of lens	3.6	"	3.2	"
Distance from cornea to posterior surface of lens	7.2	"	7.2	"
Reduced Eye.				
Radius of curvature	5.02	"	4.48	"
Distance from cornea to principal point	2.15	"	2.26	"
Distance from cornea to nodal point	7.16	"	6.74	"
Distance from cornea to anterior focus	12.918	"	11.241	"
Distance from cornea to posterior focus	22.231	"	20.248	"

It will be noticed that no change occurs in the curvature of the cornea, and next to none in the posterior surface of the lens, while the anterior surface of the lens undergoes material alterations both in its shape and position.

Associated with the accommodative movements above described, two other changes take place in the eyes to adapt them for near vision. In the first place, the axes of the eyes are converged upon the near object, so that the images formed in the two eyes shall fall upon corresponding points of the retinas, as will be more fully explained in connection with the subject of binocular vision. In the second place, the pupil becomes contracted, thus reducing the size of the pencil of rays that enters the eye. The importance of this movement of the pupil will be better understood after the subject of spherical aberration of light has been explained. These three adjustments, focal, axial, and pupillary, are so habitually associated in looking at near objects that the axial can only by an effort be dissociated from the other two, while these two are quite inseparable from one another. This may be illustrated by a simple experiment. On a sheet of paper about 40 centimeters distant

from the eyes draw two letters or figures precisely alike and about 3 centimeters apart. (Two letters cut from a newspaper and fastened to the sheet will answer the same purpose.) Hold a small object like the head of a pin between the eyes and the paper at the point of intersection of a line joining the right eye and the left letter with a line joining the left eye and the right letter. If the axes of vision are converged upon the pin-head, that object will be seen distinctly, and beyond it will be seen indistinctly *three* images of the letter, the central one being formed by the blending of the inner one of each pair of images formed on the two retinas. If now the attention be directed to the middle image, it will gradually become perfectly distinct as the eye accommodates itself for that distance. We have thus an axial adjustment for a very near object and a focal adjustment for a more distant one. If the pupil of the individual making this observation be watched by another person, it will be found that at the moment when the middle image of the letter becomes distinct the pupil, which had been contracted in viewing the pin-head, suddenly dilates. It is thus seen that when the axial and focal adjustments are dissociated from each other the pupillary adjustment allies itself with the latter.

The opposite form of dissociation—viz. the axial adjustment for distance and the focal adjustment for near vision—is less easy to bring about. It may perhaps be best accomplished by holding a pair of stereoscopic pictures before the eyes and endeavoring to direct the right eye to the right and the left eye to the left picture—*i. e.* to keep the axes of vision parallel while the eyes are accommodated for near objects. One who is successful in this species of ocular gymnastics sees the two pictures blend into one having all the appearance of a solid object. The power of thus studying stereoscopic pictures without a stereoscope is often a great convenience to the possessor, but individuals differ very much in their ability to acquire it.

Range of Accommodation.—By means of the mechanism above described it is possible for the eye to produce a distinct image upon the retina of objects lying at various distances from the cornea. The point farthest from the eye at which an object can be distinctly seen is called the *far-point*, and the nearest point of distinct vision is called the *near-point* of the eye, and the distance between the near-point and the far-point is called the range of distinct vision or the *range of accommodation.* As the normal emmetropic eye is adapted, when at rest, to bring parallel rays of light to a focus upon the retina, its far-point may be regarded as at an infinite distance. Its near-point varies with age, as will be described under Presbyopia. In early adult life it is from 10 to 13 centimeters from the eye. For every point within this range there will be theoretically a corresponding condition of the lens adapted to bring rays proceeding from that point to a focus on the retina, but as rays reaching the eye from a point 175 to 200 centimeters distant do not, owing to the small size of the pupil, differ sensibly from parallel rays, there is no appreciable change in the lens unless the object looked at lies within that distance. It is also evident that as an object approaches the eye a given change of distance will cause a constantly increasing amount of divergence of the rays proceeding from

it, and will therefore necessitate a constantly increasing amount of change in the lens to enable it to focus the rays on the retina. We find, accordingly, that all objects more than two meters distant from the eye can be seen distinctly at the same time—*i. e.* without any change in the accommodative mechanism—but for objects within that distance we are conscious of a special effort of accommodation which becomes more and more distinct the shorter the distance between the eye and the object.

Myopia and Hypermetropia.—There are two conditions of the eye in which the range of accommodation may differ from that which has just been described as normal. These conditions, which are too frequent to be regarded (except in extreme cases) as pathological, are generally dependent upon the eyeball being unduly lengthened or shortened. In Fig. 223 are shown diagrammatically the three conditions known as emmetropia, myopia, and hypermetropia. In the normal or emmetropic eye, *A*, parallel rays are represented as brought to a focus on the retina; in the short-sighted, or myopic, eye, *B*, similar rays are focussed in front of the retina, since the latter is abnormally distant; while in the over-sighted, or hypermetropic, eye, *C*, they are focussed behind the retina, since it is abnormally near.

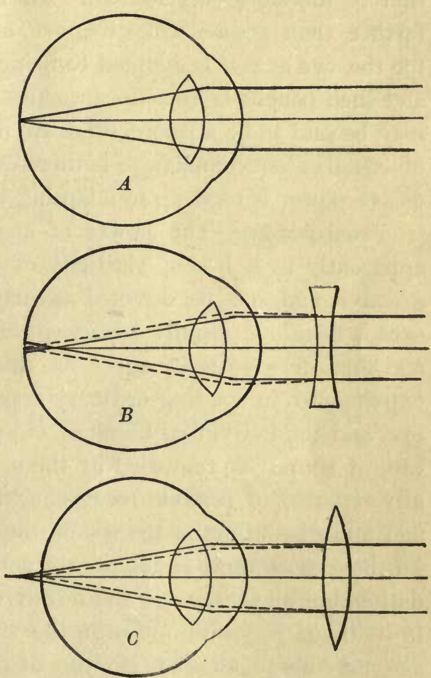


FIG. 223.—Diagram showing the difference between normal, myopic, and hypermetropic eyes.

It is evident that when the eye is at rest both the myopic and the hypermetropic eye will see distant objects indistinctly, but there is this important difference: that in hypermetropia the difficulty can be corrected by an effort of accommodation, while in myopia this is impossible, since there is no mechanism by which the radius of the lenticular surfaces can be increased. Hence an individual affected with myopia is always aware of the infirmity, while a person with hypermetropic eyes often goes through life unconscious of the defect. In this case the accomodation is constantly called into play even for distant objects, and if the hypermetropia is excessive, any prolonged use of the eyes is apt to be attended by a feeling of fatigue, headache, and a train of nervous symptoms familiar to the ophthalmic surgeon. Hence it is important to discover this defect where it exists and to apply the appropriate remedy—viz. convex lenses placed in front of the eyes in order to make the rays slightly convergent when they enter the eye. Thus aided, the refractive power of the eye at rest is sufficient to bring the rays to a focus upon the retina and thus relieve the accommoda-

tion. This action of a convex lens in hypermetropia is indicated by the dotted lines in Fig. 222, *C*, and the corresponding use of a concave lens in myopia is shown in Fig. 222, *B*.

The detection and quantitative determination of hypermetropia are best made after the accommodation has been paralyzed by the use of atropia, by ascertaining how strong a convex lens must be placed before the eye to produce distinct vision of distant objects.

The range of accommodation varies very much from the normal in myopic and hypermetropic eyes. In myopia the near-point is often 5 or 6 centimeters from the cornea, while the far-point, instead of being infinitely far off, is at a variable but no very great distance from the eye. The range of accommodation is therefore very limited. In hypermetropia the near-point is slightly farther than normal from the eye, and the far-point cannot be said to exist, for the eye at rest is adapted to bring converging rays to a focus on the retina, and such pencils of rays do not exist in nature. Mathematically, the far-point may be said to be at more than an infinite distance from the eye. The range of effective accommodation is therefore reduced, for a portion of the accommodative power is used up in adapting the eye to receive parallel rays.

Presbyopia.—The power of accommodation diminishes with age, owing apparently to a loss of elasticity of the lens. The change is regularly progressive, and can be detected as early as the fifteenth year, though in normal eyes it does not usually attract attention until the individual is between forty and forty-five years of age. At this period of life a difficulty is commonly experienced in reading ordinary type held at a convenient distance from the eye, and the individual becomes old-sighted or *presbyopic*—a condition which can, of course, be remedied by the use of convex glasses. Cases are occasionally reported of persons recovering their power of near vision in extreme old age and discontinuing the use of the glasses previously employed for reading. In these cases there is apparently not a restoration of the power of accommodation, but an increase in the refractive power of the lens through local changes in its tissue. A diminution in the size of the pupil, sometimes noticed in old age, may also contribute to the distinctness of the retinal image, as will be described in connection with spherical aberration.

Defects of the Dioptric Apparatus.—The above-described imperfections of the eye—viz. myopia and hypermetropia—being generally (though not invariably) due to an abnormal length of the longitudinal axis, are to be regarded as defects of construction affecting only a comparatively small number of eyes. There are, however, a number of imperfections of the dioptric apparatus, many of which affect all eyes alike. Of these imperfections some affect the eye in common with all optical instruments, while others are peculiar to the eye and are not found in instruments of human construction. The former class will be first considered.

Spherical Aberration.—It has been stated that a pencil of rays falling upon a spherical refracting surface will be refracted to a common focus. Strictly speaking, however, the outer rays of the pencil—*i. e.* those which fall

near the periphery of the refracting surface—will be refracted more than those which lie near the axis and will come to a focus sooner. This phenomenon, which is called spherical aberration, is more marked with diverging than with parallel rays, and tends, of course, to produce an indistinctness of the image which will increase with the extent of the surface through which the rays pass. The effect of a diaphragm used in many optical instruments to reduce the amount of spherical aberration by cutting off the side rays is shown diagrammatically in Fig. 224.

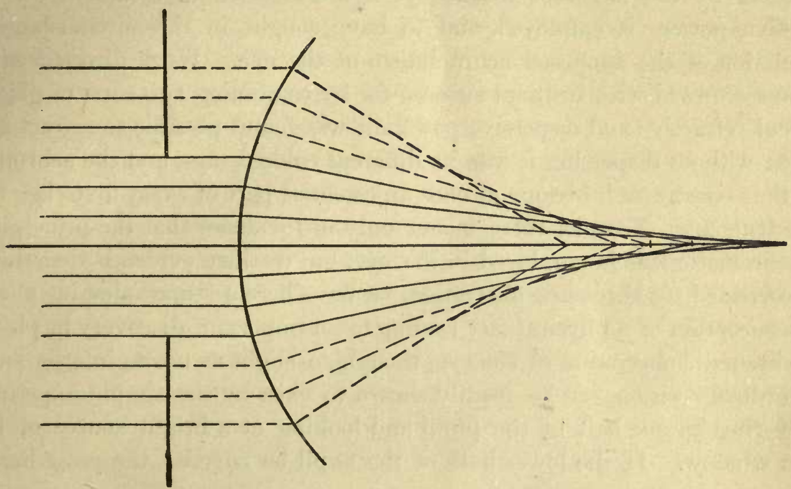


FIG. 224.—Diagram showing the effect of a diaphragm in reducing the amount of spherical aberration.

The rôle of the iris in the vision of near objects is now evident, for when the eye is directed to a near object the spherical aberration is increased in consequence of the rays becoming more divergent, but the contraction of the pupil which accompanies accommodation tends, by cutting off the side rays, to prevent a blurring of the image which otherwise would be produced. It must, however, be remembered that the crystalline lens, unlike any lens of human construction, has a greater index of refraction at the centre than at the periphery. This, of course, tends to correct spherical aberration, and, in so far as it does so, to render the cutting off of the side rays unnecessary. Indeed, the total amount of possible spherical aberration in the eye is so small that its effect on vision may be regarded as insignificant in comparison with that caused by the other optical imperfections of the eye.

Chromatic Aberration.—In the above account of the dioptric apparatus of the eye the phenomena have been described as they would occur with monochromatic light—*i. e.* with light having but one degree of refrangibility. But the light of the sun is composed of an infinite number of rays of different degrees of refrangibility. Hence when an image is formed by a simple lens the more refrangible rays—*i. e.* the violet rays of the spectrum—are brought to a focus sooner than the less refrangible red rays. The image therefore

appears bordered by fringes of colored light. This phenomenon of *chromatic aberration* can be well observed by looking at objects through the lateral portion of a simple lens, or, still better, by observing them through two simple lenses held at a distance apart equal to the sum of their focal distances. The objects will appear inverted (as through an astronomical telescope) and surrounded with borders of colored light. Now, the chromatic aberration of the eye is so slight that it is not easily detected, and the physicists of the eighteenth century, in their efforts to produce an achromatic lens, seem to have been impressed by the fact that in the eye a combination of media of different refractive powers is employed, and to have sought in this circumstance an explanation of the supposed achromatism of the eye. Work directed on this line was crowned with brilliant success, for by combining two sorts of glass of different refractive and dispersive powers it was found possible to refract a ray of light without dispersing it into its different colored rays, and the achromatic lens, thus constructed, became at once an essential part of every first-class optical instrument. Now, as there is not only no evidence that the principle of the achromatic lens is employed in the eye, but distinct evidence that the eye is uncorrected for chromatic aberration, we have here a remarkable instance of a misconception of a physical fact leading to an important discovery in physics. The chromatic aberration of the eye, though so slight as not to interfere at all with ordinary vision, can be readily shown to exist by the simple experiment of covering up one half of the pupil and looking at a bright source of light *e. g.* a window. If the lower half of the pupil be covered, the cross-bars of

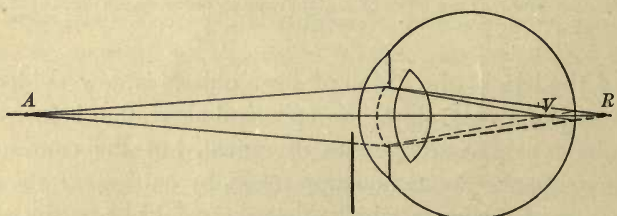


FIG. 225.—Diagram to illustrate chromatic aberration.

the window will appear bordered with a fringe of blue light on the lower and reddish light on the upper side. The explanation usually given of the way in which this result is produced is illustrated in Fig. 225. Owing to the chromatic aberration of the eye all the rays emanating from an object at *A* are not focussed accurately on the retina, but if the eye is accommodated for a ray of medium refrangibility, the violet rays will be brought to a focus in front of the retina at *V*, while the red rays will be focussed behind the retina at *R*. On the retina itself will be formed not an accurate optical image of the point *A*, but a small circle of dispersion in which the various colored rays are mixed together, the violet rays after crossing falling upon the same part of the retina as the red rays before crossing. Thus by a sort of compensation, which, however, cannot be equivalent to the synthetic reproduction of white light by the union of the spectral colors, the disturbing effect of chromatic aberration is

diminished. When the lower half of the pupil is covered by the edge of a card held in front of the cornea at D, the aberration produced in the upper half of the eye is not compensated by that of the lower half. Hence the image of a point of white light at A will appear as a row of spectral colors on the retina, and all objects will appear bordered by colored fringes. Another good illustration of the chromatic aberration of the eye is obtained by cutting two holes of any convenient shape in a piece of black cardboard and placing behind one of them a piece of blue and behind the other a piece of red glass. If the card is placed in a window some distance (10 meters) from the observer, in such a position that the white light of the sky may be seen through the colored glasses, it will be found that the outlines of the two holes will generally be seen with unequal distinctness. To most eyes the red outline will appear quite distinct, while the blue figure will seem much blurred. To a few individuals the blue figure appears the more distinct, and these will generally be found to be hypermetropic.

Astigmatism.—The defect known as astigmatism is due to irregularities of curvature of the refracting surfaces, in consequence of which all the rays proceeding from a single point cannot be brought to a single focus on the retina.

Astigmatism is said to be *regular* when one of the surfaces, generally the cornea, is not spherical, but ellipsoidal—*i. e.* having meridians of maximum

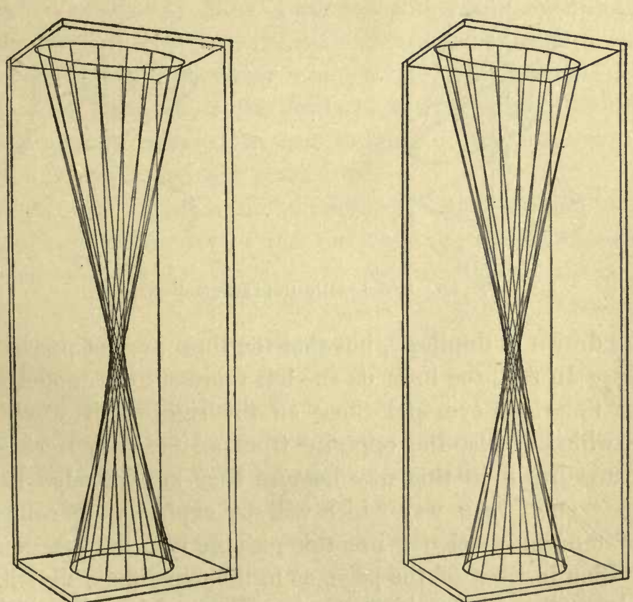


FIG. 226.—Model to illustrate astigmatism.

and minimum curvature at right angles to each other, though in each meridian the curvature is regular. When this is the case the rays proceeding from a single luminous point are brought to a focus earliest when they lie in the meridian in which the surface is most convex. Hence the pencil of rays will

have two linear foci, at right angles to the meridians of greatest and least curvature separated by a space in which a section of the cone of rays will be first elliptical, then circular, and then again elliptical. This defect exists to a certain extent in nearly all eyes, and is, in some cases, a serious obstacle to distinct vision. The course of the rays when thus refracted is illustrated in Fig. 226, which represents the interior of a box through which black threads are drawn to indicate the course of the rays of light. The threads start at one end of the box from a circle representing the cornea, and converge with different degrees of rapidity in different meridians, so that a section of the cone of rays will be successively an ellipse, a straight line, an ellipse, a circle, etc., as shown by the model represented in Fig. 227. It will be noticed that this and the preced-

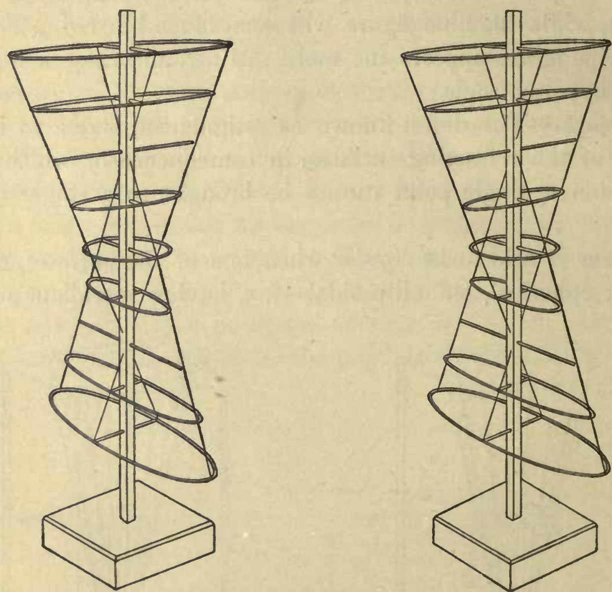


FIG. 227.—Model to illustrate astigmatism.

ing figure are drawn in duplicate, but that the lines are not precisely alike on the two sides. In fact, the lines on the left represent the model as it would be seen with the right eye, and those on the right as it would appear to the left eye, which is just the opposite from an ordinary stereoscopic slide. The figures are drawn in this way because they are intended to produce a "pseudoscopic" effect in a way which will be explained in connection with the subject of binocular vision. For this purpose it is only necessary to cross the axes of vision in front of the page, as in the experiment described on page 758, for studying the relation between the focal, axial, and pupillary adjustments of the eye. As soon as the middle image becomes distinct it assumes a stereoscopic appearance, and the correct relations between the different parts of the model are at once obvious.

This imperfection of the eye may be detected by looking at lines such as are shown in Figure 228, and testing each eye separately. If the straight lines

drawn in various directions through a common point cannot be seen with equal distinctness at the same time, it is evident that the eye is better adapted to focus rays in one meridian than in another—*i. e.* it is astigmatic. The concentric

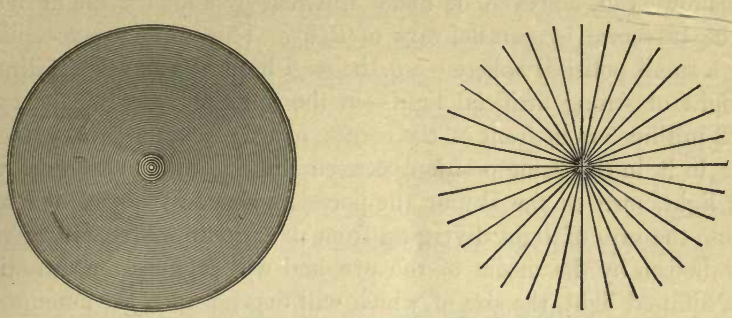


FIG. 228.—Lines for the detection of astigmatism.

circles are a still more delicate test. Few persons can look at this figure attentively without noticing that the lines are not everywhere equally distinct, but that in certain sectors the circles present a blurred appearance. Not infrequently it will be found that the blurred sectors do not occupy a constant position, but oscillate rapidly from one part of the series of circles to another. This phenomenon seems to be due to slight involuntary contractions of the ciliary muscle causing changes in accommodation.

The direction of the meridians of greatest and least curvature of the cornea of a regularly astigmatic eye, and the difference in the amount of this curvature, can be very accurately measured by means of the ophthalmometer (see p. 750). These points being determined, the defect of the eye can be perfectly corrected by cylindrical glasses adapted to compensate for the excessive or deficient refraction of the eye in certain meridians.

By another method known as "skiascopy," which consists in studying the light reflected from the fundus of the eye when the ophthalmoscopic mirror is moved in various directions, the amount and direction of the astigmatism of the eye as a whole (and not that of the cornea alone) may be ascertained.

Astigmatism is said to be irregular when in certain meridians the curvatures of the refracting surfaces are not arcs of circles or ellipses, or when there is a lack of homogeneousness in the refracting media. This imperfection exists to a greater or less extent in all eyes, and, unlike regular astigmatism, is incapable of correction. It manifests itself by causing the outlines of all brilliant objects to appear irregular. It is on this account that the fixed stars do not appear to us like points of light, but as luminous bodies with irregular "star"-shaped outlines. The phenomenon can be conveniently studied by looking at a pin-hole in a large black card held at a convenient distance between the eye and a strong light. The hole will appear to have an irregular outline, and to some eyes will appear double or treble.

Intraocular Images.—Light entering the eye makes visible, under certain circumstances, a number of objects which lie within the eye itself. These objects are usually opacities in the media of the eye which are ordinarily invisi-

ble, because the retina is illuminated by light coming from all parts of the pupil, and with such a broad source of light no object, unless it is a very large one or one lying very near the back of the eye, can cast a shadow on the retina. Such shadows can, however, be made apparent by allowing the media of the eye to be traversed by parallel rays of light. This can be accomplished by holding a small polished sphere—*e. g.* the steel head of a shawl-pin illuminated by sunlight or strong artificial light—in the anterior focus of the eye—*i. e.* about 22 millimeters in front of the cornea, or by placing a dark screen with a pin-hole in it in the same position between the eye and a source of uniform diffused light, such as the sky or the porcelain shade of a student lamp. In either case the rays of light diverging from the minute source will be refracted into parallelism by the media of the eye, and will produce the sensation of a circle of diffused light, the size of which will depend upon the amount of dilatation of the pupil. Within this circle of light will be seen the shadows of any opaque substances that may be present in the media of the eye. These shadows, being cast by parallel rays, will be of the same size as the objects themselves, as is shown diagrammatically in Figure 229, in which *A* represents a source

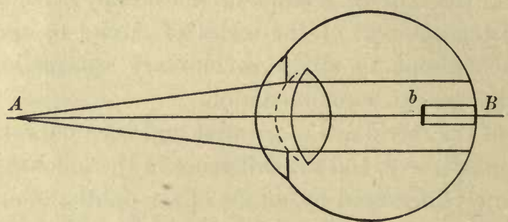


FIG. 229.—Showing the method of studying intraocular images (Helmholtz).

of light at the anterior focus of the eye, and *b* an opacity in the vitreous humor casting a shadow *B* of the same size as itself upon the retina. It is evident that if the source of light *A* is moved from side to side the various opacities will be displaced relatively to the circle of light surrounding them by an amount depending upon the distance of the opacities from the retina. A study of these displacements will therefore afford a means of determining the position of the opacities within the media of the eye.

Muscæ Volitantes.—Among the objects to be seen in thus examining the eye the most conspicuous are those known as the *muscæ volitantes.* These present themselves in the form of beads, either singly or in groups, or of streaks, patches, and granules. They have an almost constant floating motion, which is increased by the movements of the eye and head. They usually avoid the line of vision, floating away when an attempt is made to fix the sight upon them. When the eye is directed vertically, however, they sometimes place themselves directly in line with the object looked at. If the intraocular object is at the same time sufficiently near the back of the eye to cast a shadow which is visible without the use of the focal illumination, some inconvenience may thus be caused in using a vertical microscope.

A study of the motions of the *muscæ volitantes* makes it evident that the

phenomenon is due to small bodies floating in a liquid medium of a little greater specific gravity than themselves. Their movements are chiefly in planes perpendicular to the axis of vision, for when the eye is directed vertically upward they move as usual through the field of vision without increasing the distance from the retina. They are generally supposed to be the remains of the embyronic structure of the vitreous body—*i. e.* portions of the cells and fibres which have not undergone complete mucous transformation.

In addition to these floating opacities in the vitreous body various other defects in the transparent media of the eye may be revealed by the method of focal illumination. Among these may be mentioned spots and stripes due to irregularities in the lens or its capsule, and radiating lines indicating the stellate structure of the lens.

Retinal Vessels.—Owing to the fact that the blood-vessels ramify near the anterior surface of the retina, while those structures which are sensitive to light constitute the posterior layer of that organ, it is evident that light entering the eye will cast a shadow of the vessels on the light-perceiving elements of the retina. Since, however, the diameter of the largest blood-vessels is not more than one-sixth of the thickness of the retina, and the diameter of the pupil is one-fourth or one-fifth of the distance from the iris to the retina, it is evident that when the eye is directed to the sky or other broad illuminated surfaces it is only the *penumbra* of the vessels that will reach the rods and cones, the *umbra* terminating conically somewhere in the thickness of the retina. But if light is allowed to enter the eye through a pin-hole in a card held a short distance from the cornea, as in the above-described method of focal illumination, a sharply defined shadow of the vessels will be thrown on the rods and cones. Yet under these conditions the retinal vessels are not rendered visible unless the perforated card is moved rapidly to and fro, so as to throw the shadow continually on to fresh portions of the retinal surface. When this is done the vessels appear, ramifying usually as dark lines on a lighter background, but the dark lines are sometimes bordered by bright edges. It will be observed that those vessels appear most distinctly the course of which is at right angles to the direction in which the card is moved. Hence in order to see all the vessels with equal distinctness it is best to move the card rapidly in a circle the diameter of which should not exceed that of the pupil. In this manner the distribution of the vessels in one's own retina may be accurately observed, and in many cases the position of the fovea centralis may be determined by the absence of vessels from that portion of the macula lutea.

The retinal vessels may also be made visible in several other ways—*e. g.*, 1. By directing the eye toward a dark background and moving a candle to and fro in front of the eye, but below or to one side of the line of vision. 2. By concentrating a strong light by means of a lens of short focus upon a point of the sclerotic as distant as possible from the cornea. By either of these methods a small image of the external source of light is formed upon the lateral portion of the eye, and this image is the source of light which throws shadows of the retinal vessels on to the rods and cones.

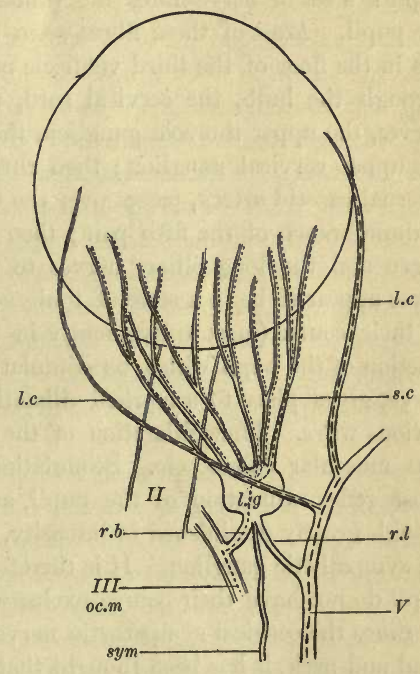
Circulation of Blood in the Retina.—When the eye is directed toward a surface which is uniformly and brightly illuminated—*e. g.* the sky or a sheet of white paper on which the sun is shining—the field of vision is soon seen to be filled with small bright bodies moving with considerable rapidity in irregular curved lines, but with a certain uniformity which suggests that their movements are confined to definite channels. They are usually better seen when one or more sheets of cobalt glass are held before the face, so that the eyes are bathed in blue light. That the phenomenon depends upon the circulation of the blood globules in the retina is evident from the fact that the moving bodies follow paths which correspond with the form of the retinal capillaries as seen by the methods above described, and also from the correspondence between the rate of movement of the intraocular image and the rapidity of the capillary circulation in those organs in which it can be directly measured under the microscope. The exact way in which the moving globules stimulate the retina so as to produce the observed phenomenon must be regarded as an unsettled question.

We have thus seen that the eye, regarded from the optician's point of view, has not only all the faults inherent in optical instruments generally, but many others which would not be tolerated in an instrument of human construction. Yet with all its imperfections the eye is perhaps the most wonderful instance in nature of the development of a highly specialized organ to fulfil a definite purpose. In the accomplishment of this object the various parts of the eye have been perfected to a degree sufficient to enable it to meet the requirements of the nervous system with which it is connected, and no farther. In the ordinary use of the eye we are unconscious of its various irregularities, shadows, opacities, etc., for these imperfections are all so slight that the resulting inaccuracy of the image does not much exceed the limit which the size of the light-perceiving elements of the retina imposes upon the delicacy of our visual perceptions, and it is only by illuminating the eye in some unusual way that the existence of these imperfections can be detected. In other words, the eye is as good an optical instrument as the nervous system can appreciate and make use of. Moreover, when we reflect upon the difficulty of the problem which nature has solved, of constructing an optical instrument out of living and growing animal tissue, we cannot fail to be struck by the perfection of the dioptric apparatus of the eye as well as by its adaptation to the needs of the organism of which it forms a part.

Iris.—The importance of the iris as an adjustable diaphragm for cutting off side rays and thus securing good definition in near vision has been described in connection with the act of accommodation. Its other function of protecting the retina from an excess of light is no less important, and we must now consider how this pupillary adjustment may be studied and by what mechanism it is effected. The changes in the size of the pupil may be conveniently observed in man and animals by holding a millimeter scale in front of the eye and noticing the variations in the diameter of the pupil. It should be borne in mind that the iris, seen in this way, does not appear in its natural size and

position, but somewhat enlarged and bulged forward by the magnifying effect of the cornea and the aqueous humor. The changes in one's own pupil may be readily observed by noticing the varying size of the circle of light thrown upon the retina when the eye is illuminated by a point of light held at the anterior focus, as in the method above described for the study of intraocular images.

The muscles of the iris are, except in birds, of the unstriped variety, and are arranged concentrically around the pupil. Radiating fibres are also recognized by many observers, though their existence has been called in question by others. The circular or constricting muscles of the iris are under the control of the third pair of cranial nerves, and are normally brought into activity in consequence of light falling upon the retina. This is a reflex phenomenon, the optic nerve being the afferent, and the third pair, the ciliary ganglion, and the short ciliary nerves the efferent, channel, as indicated in Figure 230. This reflex is in man and many of the higher animals bilateral—*i. e.* light falling upon one retina will cause a contraction of both pupils. This may readily be observed in one's own eye when focally illuminated in the manner above described. Opening the other eye will, under these conditions, cause a diminution, and closing it an increase, in the size of the circle of light. This bilateral character is found to be dependent upon the nature of the decussation of the optic nerves, for in animals in which the crossing is complete the reflex is confined to the illuminated eye. The arrangement of the fibres in the optic commissure is in general associated with the position of the eyes in the head. When the eyes are so placed that they can both be directed to the same object, as in man and many of the higher animals, the fibres of each optic nerve are usually found to be distributed to both optic tracts, while in animals whose eyes are in opposite sides of the head there is complete crossing of the optic nerves. Hence it may be said that animals having binocular vision have in general a bilateral pupillary reflex. The rule is, however, not without exceptions, for owls, though their visual axes are parallel, have, like other birds, a com-



Course of constrictor nerve-fibres ....
" dilator " - - - - - - -

FIG. 230.—Diagrammatic representation of the nerves governing the pupil (after Foster): *II*, optic nerve; *l. g*, ciliary ganglion; *r. b*, its short root from *III*, motor-oculi nerve; *sym*, its sympathetic root; *r. l*, its long root from *V*, ophthalmo-nasal branch of ophthalmic division of fifth nerve; *s. c*, short ciliary nerves; *l. c*, long ciliary nerves.

plete crossing of the optic nerves, and consequently a unilateral pupillary reflex.[1]

A direct as well as a reflex constriction of the pupil under the influence of light has been observed in the excised eyes of eels, frogs, and some other animals. As the phenomenon can be seen in preparations consisting of the iris alone or of the iris and cornea together, it is evident that the light exerts its influence directly upon the tissues of the iris and not through an intraocular connection with the retina. The maximum effect is produced by the yellowish-green portion of the spectrum.

Antagonizing the motor oculi nerve in its constricting influence on the pupil is a set of nerve-fibres the function of which is to increase the size of the pupil. Most of these fibres seem to run their course from a centre which lies in the floor of the third ventricle not far from the origin of the third pair, through the bulb, the cervical cord, the anterior roots of the upper dorsal nerves, the upper thoracic ganglion, the cervical sympathetic nerve as far as the upper cervical ganglion; then through a branch which accompanies the internal carotid artery, passes over the Gasserian ganglion and joins the ophthalmic branch of the fifth pair; then through the nasal branch of the latter nerve and the long ciliary nerves to the eye[2] (see diagram, p. 769). These fibres appear to be in a state of tonic activity, for section of them in any part of their course (most conveniently in the cervical sympathetic) causes a contraction of the pupil which, on stimulation of the peripheral end of the divided nerve, gives place to a marked dilatation. Their activity can be increased in various ways. Thus dilatation of the pupil may be caused by dyspnea, violent muscular efforts, etc. Stimulation of various sensory nerves may also cause reflex dilatation of the pupil, and this phenomenon may be observed, though greatly diminished in intensity, after extirpation of the superior cervical sympathetic ganglion. It is therefore evident that the dilator nerves of the pupil do not have their course exclusively in the cervical sympathetic nerve.

Since the cervical sympathetic nerve contains vaso-constrictor fibres for the head and neck, it has been thought that its dilating effect upon the pupil might be explained by its power of causing changes in the amount of blood in the vessels of the iris. There is no doubt that a condition of vascular turgescence or depletion will tend to produce contraction or dilatation of the pupil, but it is impossible to explain the observed phenomena in this way, since the pupillary are more prompt than the vascular changes, and may be observed on a bloodless eye. Moreover, the nerve-fibres producing them are said to have a somewhat different course. Another explanation of the influence of the sympathetic on the pupil is that it acts by inhibiting the contraction of the sphincter muscles, and that the dilatation is simply an elastic reaction. But since it is posssible to produce local dilatation of the pupil by circumscribed stimulation at or near

[1] Steinach: *Archiv für die gesammte Physiologie*, xlvii. 313.

[2] Langley: *Journal of Physiology*, xiii. p. 575. For the evidence of the existence of a "cilio-spinal" centre in the cord, see Steil and Langendorff: *Archiv für die gesammte Physiologie*, lviii. p. 155; also Schenck: *Ibid.*, lxii. p. 494.

the outer border of the iris, it seems more reasonable to conclude that the dilator nerves of the pupil act upon radial muscular fibres in the substance of the iris, in spite of the fact that the existence of such fibres has not been universally admitted.

Whatever view may be taken of the mechanism by which the sympathetic nerves influence the pupil, there is no doubt that the iris is under the control of two antagonistic sets of nerve-fibres, both of which are, under normal circumstances, in a state of tonic activity. Therefore, when the sympathetic nerve is divided the pupil contracts under the influence of the motor oculi, and section of the motor oculi causes dilatation through the unopposed influence of the sympathetic.

The movements of the iris, though performed by smooth muscles, are more rapid than those of smooth muscles found elsewhere—*e. g.* in the intestines and the arteries. The contraction of the pupil when the retina of the opposite eye is illuminated occupies about 0.3″; the dilatation when the light is cut off from the eye, about 3″ or 4″. The latter determination is, however, difficult to make with precision, since dilatation of the pupil takes place at first rapidly and then more slowly, so that the moment when the process is at an end is not easily determined. After remaining a considerable time in absolute darkness the pupils become enormously dilated, as has been shown by flash-light photographs taken under these conditions. In sleep, though the eyes are protected from the light, the pupils are strongly contracted, but dilate on stimulation of sensory nerves, even though the stimulation may be insufficient to rouse the sleeper.

Many drugs when introduced into the system or applied locally to the conjunctiva produce effects upon the pupil. Those which dilate it are known as *mydriatics*, those which contract it as *myotics*. Of the former class the most important is atropin, the alkaloid of the Atropa belladonna, and of the latter physostigmin, the alkaloid of the Calabar bean. In addition to their action upon the pupil, mydriatics paralyze the accommodation, thus focussing the eye for distant objects, while myotics, by producing a cramp of the ciliary muscle, adjust the eye for near vision. The effect on the accommodation usually begins later and passes off sooner than the affection of the pupil. Atropin seems to act by producing local paralysis of the terminations of the third pair of cranial nerves in the sphincter iridis and the ciliary muscle. In large doses it may also paralyze the muscle-fibres of the sphincter. With this paralyzing action there appears to be combined a stimulating effect upon the dilator muscles of the iris. The myotic action of physostigmin seems to be due to a local stimulation of the fibres of the sphincter of the iris.

Although in going from a dark room to a lighter one the pupil at first contracts, this contraction soon gives place to a dilatation, and in about three or four minutes the pupil usually regains its former size. In a similar manner the primary dilatation of the pupil caused by entering a dark room from a lighter one is followed by a contraction which usually restores the pupil to its original size within fifteen or twenty minutes. It is thus evident that the

amount of light falling upon the retina is not the only factor in determining the size of the pupil. In fact, if the light acts for a sufficient length of time the pupil may have the same size under the influence of widely different degrees of illumination.[1]

This so-called "adaptation" of the eye to various amounts of light seems to be connected with the movements of the retinal pigment-granules and with the chemical changes of the visual purple, to be more fully described in connection with the physiology of the retina.

The Ophthalmoscope.—Under normal conditions the pupil of the eye appears as a black spot in the middle of the colored iris. The cause of this dark appearance of the pupil is to be found in the fact that a source of light and the retina lie in the conjugate foci of the dioptric apparatus of the eye. Hence any light entering the eye that escapes absorption by the retinal pigment and is reflected from the fundus must be refracted back to the source from which it came. The eye of an observer who looks at the pupil from another direction will see no light coming from it, and it will therefore appear to him black. It is therefore evident that the essential condition for perceiving light coming from the fundus of the eye is that the line of vision of the observing eye shall be in the line of illumination. This condition is fulfilled by means of instruments known as ophthalmoscopes. The principles involved in the construction of the most common form of ophthalmoscope are illustrated diagrammatically in Figure 231.

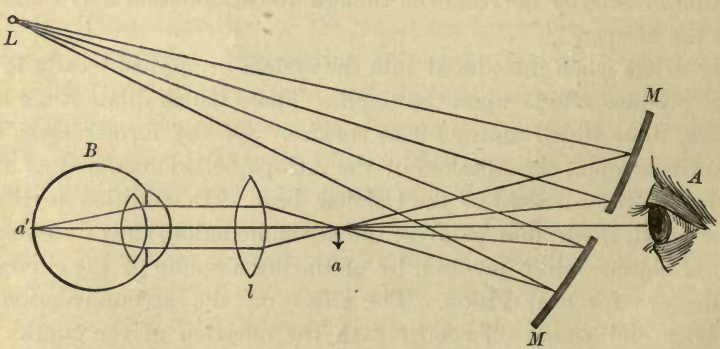


FIG. 231.—Diagram to illustrate the principles of a simple ophthalmoscope (after Foster).

The rays from a source of light L, after being brought to a focus at a by the concave perforated mirror M M, pass on and are rendered parallel by the lens l. Then, entering the observed eye B, they are brought to a focus on the retina at a'. Any rays which are reflected back from the part of the retina thus illuminated will follow the course of the entering rays and be brought to a focus at a. The eye of an observer at A, looking through the hole in the mirror, will therefore see at a an inverted image of the retina, the observation of which may be facilitated by a convex lens placed immediately in front of the observer's eye.

[1] Schirmer: *Archiv für Ophthalmologie*, xi. 5.

The fundus of the eye thus observed presents a reddish background on which the retinal vessels are distinctly visible.

Retina.—Having considered the mechanism by which optical images of objects at various distances from the eye are formed upon the retina, we must next inquire what part of the retina is affected by the rays of light, and in what this affection consists. To the former of these questions it will be found possible to give a fairly satisfactory answer. With regard to the latter nothing positive is known.

The structure of the retina is exceedingly complicated, but, as very little is known of the functions of the ganglion cells and of the molecular and nuclear layers, it will suffice for the present purpose of physiological description to regard the retina as consisting of fibres of the optic nerve which are connected through various intermediate structures with the layer of rods and cones.

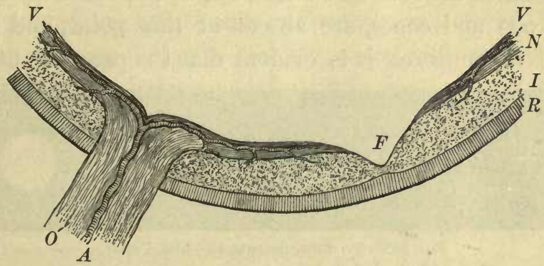


FIG. 232.—Diagrammatic representation of the retina.

Figure 232 is intended to show, diagrammatically, the mutual relation of these various portions of the retina in different parts of the eye, and is not drawn to scale. It will be observed that the optic nerve *O*, where it enters the eye, interrupts the continuity of the layer of rods and cones *R* and of the intermediate structures *I*. Its fibres spread themselves out in all directions, forming the internal layer of the retina *N*. The central artery of the retina *A* accompanying the optic nerve ramifies in the layer of nerve-fibres and in the immediately adjacent layers of the retina, forming a vascular layer *V*. In the fovea centralis *F* of the macula lutea (the centre of distinct vision) the layer of rods and cones becomes more highly developed, while the other layers of the retina are much reduced in thickness and the blood-vessels entirely disappear. This histological observation points strongly to the conclusion that the rods and cones are the structures which are essential to vision, and that in them are found the conditions for the conversion of the vibrations of the luminiferous ether into a stimulus for a nerve-fibre. This view derives confirmation from the observations on the retinal blood-vessels, for it is found that the distance between the vascular layer of the retina and the layer of rods and cones determined by histological methods corresponds with that which must exist between the vessels and the light-perceiving elements of the retina, as calculated from the apparent displacement of the shadow caused by given movements of the source of light used in studying intraocular images[1] as

[1] "Dimmer Verh. d. phys. Clubs zu Wien, 24 April, 1894," *Centralbl. für Physiologie*, 1894, 159.

described on p. 767. Another argument in favor of this view is found in the correspondence between the size of the smallest visible images on the retina and the diameter of the rods and cones. A double star can be recognized as double by the normal eye when the distance between the components corresponds to a visual angle of 60″. Two white lines on a black ground are seen to be distinct when the distance between them subtends a visual angle of 64″–73″. These angles correspond to a retinal image of 0.0044, 0.0046, and 0.0053 millimeter. Now, the diameter of the cones in the macula lutea, as determined by Kölliker, is 0.0045–0.0055 millimeter, a size which agrees well with the hypothesis that each cone when stimulated can produce a special sensation of light distinguishable from those caused by the stimulation of the neighboring cones. The existence of the so-called blind spot in the retina at the point of entrance of the optic nerve is sometimes regarded as evidence of the light-perceiving function of the rods and cones, but as the other layers of the retina, as well as the rods and cones, are absent at this point, and the retina here consists solely of nerve-fibres, it is evident that the presence of the blind spot

FIG. 233.—To demonstrate the blind spot.

only proves that the optic nerve-fibres are insensible to light. Figure 233 is intended to demonstrate this insensibility. For this purpose it should be held at a distance of about 23 centimeters from the eyes (*i. e.* about 3.5 times the distance between the cross and the round spot). If the left eye be closed and the right eye fixed upon the cross, the round spot will disappear from view, though it will become visible if the eye be directed either to the right or to the left of the cross, or if the figure be held either a greater or a less distance from the eye. The size and shape of the blind spot may readily be determined as follows: Fix the eye upon a definite point marked upon a sheet of white paper. Bring the black point of a lead pencil (which, except the point, has been painted white or covered with white paper) into the invisible portion of the field of vision and carry it outward in any direction until it becomes visible. Mark upon the paper the point at which it just begins to be seen, and by repeating the process in as many different directions as possible the outline of the blind spot may be marked out. Figure 234 shows the shape of the blind spot determined by Helmholtz in his own right eye, *a* being the point of fixation of the eye, and the line *A B* being one-third of the distance between the eye and the paper. The irregularities of outline, as at

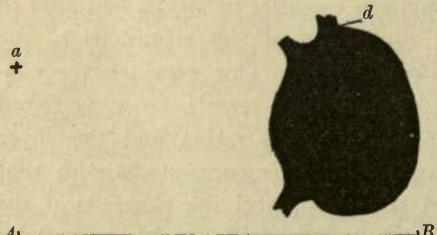


FIG. 234.—Form of the blind spot (Helmholtz).

d, are due to shadows of the large retinal vessels. During this determination it is of course necessary that the head should occupy a fixed position with regard to the paper. This condition can be secured by holding firmly between the teeth a piece of wood that is clamped in a suitable position to the edge of the table. The diameter of the blind spot, as thus determined, has been found to correspond to a visual angle varying from 3° 39′ to 9° 47′, the average measurement being 6° 10′. This is about the angle that is subtended by the human face seen at a distance of two meters. Although a considerable portion of the retina is thus insensible to light, we are, in the ordinary use of the eyes, conscious of no corresponding blank in the field of vision. By what psychical operation we "fill up" the gap in our subjective field of vision caused by the blind spot of the retina is a question that has been much discussed without being definitely settled.

The above-mentioned reasons for regarding the rods and cones as the light-perceiving elements of the retina seem sufficiently conclusive. Whether there is any difference between the rods and the cones with regard to their light-perceiving function is a question which may be best considered in connection with a description of the qualitative modifications of light.

The histological relation between the various layers of the retina is still under discussion. According to recent observations of Cajal,[1] the connection between the rods and cones on the one side and the fibres of the optic nerve on the other is established in a manner which is represented diagrammatically in Figure 235. The prolongations of the bipolar cells of the internal nuclear layer *E* break up into fine fibres in the external molecular (or plexiform) layer *C*. Here they are brought into contact, though not into anatomical continuity, with the terminal fibres of the rods and cones. The inner prolongations of the same bipolar cells penetrate into the internal molecular (or plexiform) layer *F*, and there come into contact with the dendrites coming from the layer of ganglion-cells *G*. These cells are, in their turn, connected by their axis-cylinder processes with the fibres of the optic nerve. The bipolar cells which serve as connective links between the rods and the optic nerve-fibres are anatomically distinguishable (as indicated in the diagram)

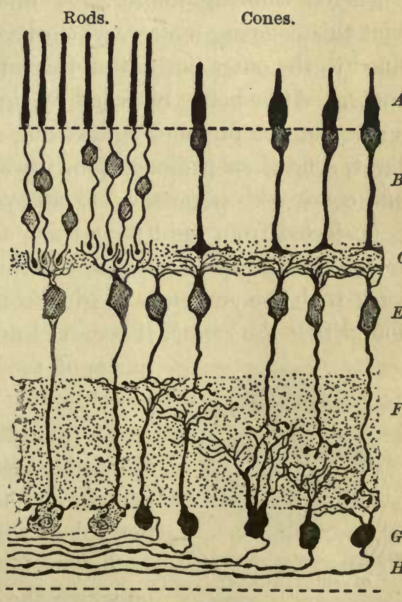


FIG. 235.—Diagrammatic representation of the structure of the retina (Cajal): *A*, layer of rods and cones; *B*, external nuclear layer; *C*, external molecular (or plexiform) layer; *E*, internal nuclear layer; *F*, internal molecular (or plexiform) layer; *G*, layer of ganglion-cells; *H*, layer of nerve-fibres.

[1] *Die Retina der Wirbelthiere*, Wiesbaden, 1894.

from those which perform the same function for the cones. Whatever be the precise mode of connection between the rods and cones and the fibres of the optic nerve, it is evident that each retinal element cannot be connected with the nerve-centres by a separate independent nerve-channel, since the retina contains many millions of rods and cones, while the optic nerve has only about 438,000 nerve-fibres,[1] though of course such a connection may exist in the fovea centralis, as Cajal has shown is probably the case in reptiles and birds.

Changes Produced in the Retina by Light.—We must now inquire what changes can be supposed to occur in the rods and cones under the influence of light by means of which they are able to transform the energy of the ether vibrations into a stimulus for the fibres of the optic nerve. Though in the present state of our knowledge no satisfactory answer can be given to this question, yet certain direct effects of light upon the retina have been observed which are doubtless associated in some way with the transformation in question.

The retina of an eye which has been protected from light for a considerable length of time has a purplish-red color, which upon exposure to light changes to yellow and then fades away. This bleaching occurs also in monochromatic light, the most powerful rays being those of the greenish-yellow portion of the spectrum—*i. e.* those rays which are most completely absorbed by the purplish-red coloring matter. A microscopic examination of the retina shows that this coloring matter, which has been termed *visual purple*, is entirely confined to the outer portion of the retinal rods and does not occur at all in the cones. After being bleached by light it is, during life, restored through the agency of the pigment epithelium, the cells of which, under the influence of light, send their prolongations inward to envelop the outer limbs of the rods and cones with pigment. If an eye, either excised or in its natural position, is protected from light for a time, and then placed in such a position that the image of a lamp or a window is thrown upon the retina for a time which may vary with the amount of light from seven seconds to ten minutes, it will be found that the retina, if removed and examined under red light, will show the image of the luminous object impressed upon it by the bleaching of the visual purple.

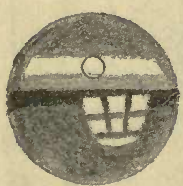


FIG. 236.—Optogram in eye of rabbit (Kühne).

If the retina be treated with a 4 per cent. solution of alum, the restoration of the visual purple will be prevented, and the so-called "optogram" will be, as photographers say, "fixed."[2]

Figure 236 shows the appearance of a rabbit's retina on which the optogram of a window has been impressed.

Although the chemical changes in the visual purple under the influence of light seem, at first sight, to afford an explanation of the transformation of the vibrations of the luminiferous ether into a stimulation for the optic nerve, yet the fact that vision is most distinct in the fovea centralis of the retina, which,

[1] Salzer: *Wiener Sitzungsberichte*, 1880, Bd. lxxxi. S. 3.

[2] Kühne: *Untersuchungen a. d. phys. Inst. d. Universität Heidelberg*, i. 1.

as it contains no rods, is destitute of visual purple, makes it impossible to regard this coloring matter as essential to vision. The most probable theory of its function is perhaps that which connects it with the adaptation of the eye to varying amounts of light, as described on p. 772.

In addition to the above-mentioned movements of the pigment epithelium cells under the influence of light, certain changes in the retinal cones of frogs and fishes have been observed.[1] The change consists in a shortening and thickening of the inner portion of the cones when illuminated, but the relation of the phenomenon to vision has not been explained.

Like most of the living tissues of the body, the retina is the seat of electrical currents. In repose the fibres of the optic nerve are said to be positive in relation to the layer of rods and cones. When light falls upon the retina this current is at first increased and then diminished in intensity.

Sensation of Light.—Whatever view may be adopted with regard to the mechanism by which light is enabled to become a stimulus for the optic nerve, the fundamental fact remains that the retina (and in all probability the layer of rods and cones in the retina) alone supplies the conditions under which this transformation of energy is possible. But in accordance with the "law of specific energy" a sensation of light may be produced in whatever way the optic nerve be stimulated, for a stimulus reaching the visual centres through the optic nerve is interpreted as a visual sensation, in the same way that pressure on a nerve caused by the contracting cicatrix of an amputated leg often causes a painful sensation which is referred to the lost toes to which the nerve was formerly distributed. Thus local pressure on the eyeball by stimulating the underlying retina causes luminous sensations, already described as "phosphenes," and electrical stimulation of the eye as a whole or of the stump of the optic nerve after the removal of the eye is found to give rise to sensations of light.

Vibrations of the luminiferous ether constitute, however, the normal stimulus of the retina, and we must now endeavor to analyze the sensation thus produced. In the first place, it must be borne in mind that the so-called ether waves differ among themselves very widely in regard to their rate of oscillation. The slowest known vibrations of the ether molecules have a frequency of about 107,000,000,000,000 in a second, and the fastest a rate of about 40,000,000,000,000,000 in a second—a range, expressed in musical terms, of about eight and one-half octaves. All these ether waves are capable of warming bodies upon which they strike and of breaking up certain chemical combinations, the slowly vibrating waves being especially adapted to produce the former and the rapidly vibrating ones the latter effect. Certain waves of intermediate rates of oscillation—viz. those ranging between 392,000,000,000,000 and 757,000,000,000,000 in a second—not only produce thermic and chemical effects, but have the power, when they strike the retina, of causing changes in the layer of rods and cones, which, in their turn, act as a stimulus to the optic nerve. The ether waves which produce these various phenomena

[1] Engelmann: *Archiv für die gesammte Physiologie*, xxxv. 498.

are often spoken of as heat rays, light rays, and actinic or chemical rays, but it must be remembered that the same wave may produce all three classes of phenomena, the effect depending upon the nature of the substance upon which it strikes. It will be observed that the range of vibrations capable of affecting the retina is rather less than one octave, a limitation which obviously tends to reduce the amount of chromatic aberration.

In this connection it is interesting to notice that the highest audible note is produced by about 40,000 sonorous impulses in a second. Between the highest audible note and the lowest visible color there is a gap of nearly thirty-four octaves in which neither the vibrations of the air nor those of the luminiferous ether affect our senses. Even if the slowly vibrating heat-rays which affect our cutaneous nerves are taken into account, there still remain over thirty-one octaves of vibrations, either of the air or of the luminiferous ether, which may be, and very likely are, filling the universe around us without in any way impressing themselves upon our consciousness.

Qualitative Modifications of Light.—All the ethereal vibrations which are capable of affecting the retina are transmitted with very nearly the same rapidity through air, but when they enter a denser medium the waves having a rapid vibration are retarded more than those vibrating more slowly. Hence when a ray of sunlight composed of all the visible ether waves strikes upon a plane surface of glass, the greater retardation of the waves of rapid vibration causes them to be more refracted than those of slower vibration, and if the glass has the form of a prism, as shown in Figure 237, this so-called "dispersion" of the rays is still further increased when the rays leave the glass, so that the emerging beam, if received upon a white surface, instead of forming a spot of white light, produces a band of color known as the solar spectrum. The colors of the spectrum, though commonly spoken of as seven in number, really form a continuous series from the extreme red to the extreme violet, these colors corresponding to ether vibrations have rates of 392,000,000,000,000 and 757,000,000,000,000 in 1 second, and wave lengths of 0.7667 and 0.3970 micromillimeters[1] respectively.

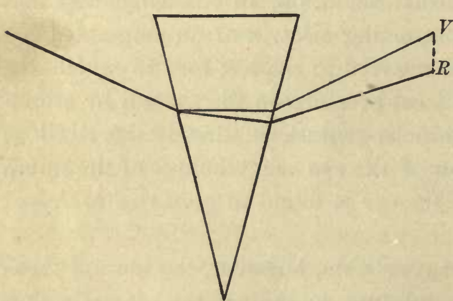


FIG. 237.—Diagram illustrating the dispersion of light by a prism.

Colors, therefore, are sensations caused by the impact upon the retina of certain ether waves having definite frequencies and wave-lengths, but these are not the only peculiarities of the ether vibration which influence the retinal sensation. The energy of the vibration, or the *vis viva* of the vibrating molecule, determines the "intensity" of the sensation or the brilliancy of the light.[2]

[1] One micromillimeter = 0.001 millimeter = one μ.

[2] The energy of vibration capable of producing a given subjective sensation of intensity varies with the color of the light, as will be later explained (see p. 786).

Furthermore, the sensation produced by the impact of ether waves of a definite length will vary according as the eye is simultaneously affected by a greater or less amount of white light. This modification of the sensation is termed its degree of "saturation," light being said to be completely saturated when it is "monochromatic" or produced by ether vibrations of a single wave-length.

The modifications of light which taken together determine completely the character of the sensation are, then, three in number—viz.: 1. Color, dependent upon rate of vibration or length of the ether wave; 2. Intensity, dependent upon the energy of the vibration; 3. Saturation, dependent upon the amount of white light mingled with the monochromatic light. These three qualitative modifications of light must now be considered in detail.

Color.—In our profound ignorance of the nature of the process by which, in the rods and cones, the movements of the ether waves are converted into a stimulus for the optic nerve-fibres, all that can be reasonably demanded of a color theory is that it shall present a logically consistent hypothesis to account for the sensations actually produced by the impact of ether waves of varying rates, either singly or combined, upon different parts of the retina. Some of the important phenomena of color sensation of which every color theory must take account may be enumerated as follows:

1. Luminosity is more readily recognized than color. This is shown by the fact that a colored object appears colorless when it is too feebly illuminated, and that a spectrum produced by a very feeble light shows variations of intensity with a maximum nearer than normal to the blue end, but no gradations of color. A similar lack of color is noticed when a colored object is observed for too short a time or when it is of insufficient size. In all these respects the various colors present important individual differences which will be considered later,

2. Colored objects seen with increasing intensity of illumination appear more and more colorless, and finally present the appearance of pure white. Yellow passes into white more readily than the other colors.

3. The power of the retina to distinguish colors diminishes from the centre toward the periphery, the various colors, in this respect also, differing materially from each other. Sensibility to red is lost at a short distance from the macula lutea, while the sensation of blue is lost only on the extreme lateral portions of the retina. The relation of this phenomenon to the distribution of the rods and cones in the retina will be considered in connection with the perception of the intensity of light.

Color-mixture.—Since the various spectral colors are produced by the dispersion of the white light of the sun, it is evident that white light may be reproduced by the reunion of the rays corresponding to the different colors, and it is accordingly found that if the colored rays emerging from a prism, as in Fig. 237, are reunited by suitable refracting surfaces, a spot of white light will be produced similar to that which would have been caused by the original beam of sunlight. But white light may be produced not only by the union of *all* the spectral colors, but by the union of certain selected colors in twos, threes,

fours, etc. Any two spectral colors which by their union produce white are said to be "complementary" colors. The relation of these pairs of complementary colors to each other may be best understood by reference to Figure 238.

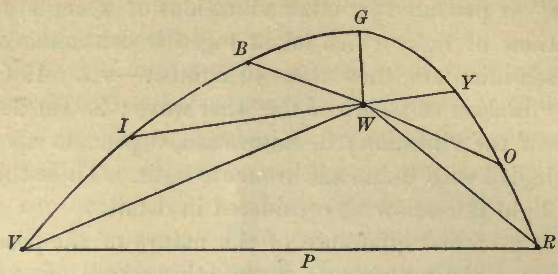


Fig. 238.—Color diagram.

Here the spectral colors are supposed to be disposed around a curved line, as indicated by their initial letters, and the two ends of the curve are united by a straight line, thus enclosing a surface having somewhat the form of a triangle with a rounded apex. If the curved edge of this surface be supposed to be loaded with weights proportionate to the luminosity of the different colors, the centre of gravity of the surface will be near the point *W*. Now, if a straight line be drawn from any point on the curved line through the point *W* and prolonged till it cuts the curve again, the colors corresponding to the two ends of this straight line will be complementary colors. Thus in Figure 238 it will be seen that the complementary color of red is bluish-green, and that of yellow lies near the indigo. It is also evident that the complementary color of green is purple, which is not a spectral color at all, but a color obtained by the union of violet and red. The union of a pair of colors lying nearer together than complementary colors produces an intermediate color mixed with an amount of white which is proportionate to the nearness of the colors to the complementary. Thus the union of red and yellow produces orange, but a less saturated orange than the spectral color. The union of two colors lying farther apart than complementary colors produces a color which borders more or less upon purple.

The mixing of colors to demonstrate the above-mentioned effects may be accomplished in three different ways:

1. By employing two prisms to produce two independent spectra, and then directing the colored rays which are to be united so that they will illuminate the same white surface.

2. By looking obliquely through a glass plate at a colored object placed behind it, while at the same time light from another colored object, placed in front of the glass, is reflected into the eye of the observer, as shown in Figure 239. Here the transmitted light from the colored object *A* and the reflected light from the colored object *B* enter the eye at *C* from the same direction, and are therefore united upon the retina.

3. By rotating before the eye a disk on which the colors to be united are

painted upon different sectors. This is most readily accomplished by using a number of disks, each painted with one of the colors to be experimented with, and each divided radially by a cut running from the centre to the circumference. The disks can then be lapped over each other and rotated together, and in this way two or more colors can be mixed in any desired proportions. This method of mixing colors depends upon the property of the retina to retain an impression after the stimulus causing it has ceased to act—a phenomenon of great importance in physiological optics, and one which will be further discussed in connection with the subject of "after-images."

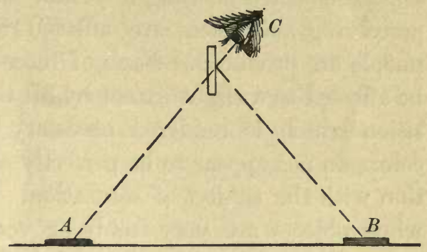


FIG. 239.—Diagram to illustrate color mixture by reflected and transmitted light (Helmholtz).

The physiological mixing of colors cannot be accomplished by the mixture of pigments or by allowing sunlight to pass successively through glasses of different colors, for in these cases rays corresponding to certain colors are absorbed by the medium through which the white light passes, and the phenomenon is the result of a process of subtraction and not addition. Light reaching the eye through red glass, for instance, looks red because all the rays except the red rays are absorbed, and light coming through green glass appears green for a similar reason. Now, when light is allowed to pass successively through red and green glass the only rays which pass through the red glass will be absorbed by the green. Hence no light will pass through the combination of red and green glass, and darkness results. But when red and green rays are mixed by any of the three methods above described the result of this process of addition is not darkness, but a yellow color, as will be understood by reference to the color diagram on p. 780. In the case of colored pigments similar phenomena occur, for here too light reaches the eye after rays of certain wave-lengths have been absorbed by the medium. This subject will be further considered in connection with color-theories.

Color-theories.—From what has been said of color-mixtures it is evident that every color sensation *may* be produced by the mixture of a number of other color sensations, and that *certain* color sensations—viz. the purples—can be produced *only* by the mixture of other sensations, since there is no single wave-length corresponding to them. Hence the hypothesis is a natural one that *all* colors are produced by the mixture in varying proportions of a certain number of fundamental colors, each of which depends for its production upon the presence in the retina of a certain substance capable of being affected (probably through some sort of a photo-chemical process) by light of a certain definite wave-length. A hypothesis of this sort lies at the basis of both the Young-Helmholtz and the Hering theories of color sensation.

The former theory postulates the existence in the retina of three substances capable of being affected by red, green, and violet rays, respectively—*i. e.* by the three colors lying at the three angles of the color diagram given on p. 780

—and regards all other color sensations as produced by the simultaneous affection of two of these substances in varying proportions. Thus when a ray of blue light falls on the retina it stimulates the violet- and green-perceiving substances, and produces a sensation intermediate between the two, while simultaneous stimulation of the red- and green-perceiving substances produces the sensations corresponding to yellow and orange; and when the violet- and red-perceiving substances are affected at the same time, the various shades of purple are produced. Each of these three substances is, however, supposed to be affected to a slight extent by all the rays of the visible spectrum, a supposition which is rendered necessary by the fact that even the pure spectral colors do not appear to be perfectly saturated, as will be explained in connection with the subject of saturation. Furthermore, the disappearance of color when objects are very feebly or very brightly illuminated or when they are seen with the lateral portions of the retina (as described on p. 779) necessitates the additional hypotheses that these three substances are all equally affected by all kinds of rays when the light is of either very small or very great intensity or when it falls on the extreme lateral portions of the retina, and that they manifest their specific irritability for red, green, and violet rays respectively only in light of moderate intensity falling not too far from the fovea centralis of the retina.

The modifications of the Young-Hemholtz theory introduced by these subsidiary hypotheses greatly diminish the simplicity which was its chief claim to acceptance when originally proposed. Moreover, there will always remain a psychological difficulty in supposing that three sensations so different from each other as those of red, green, and violet can by their union produce a fourth sensation absolutely distinct from any of them—viz. white.

The fact that in the Hering theory this difficulty is obviated has contributed greatly to its acceptance by physiologists. In this theory the retina is supposed to contain three substances in which chemical changes may be produced by ether vibrations, but each of these substances is supposed to be affected in two opposite ways by rays of light which correspond to complementary color sensations. Thus in one substance—viz. the white-black visual substance—katabolic or destructive changes are supposed to be produced by all the rays of the visible spectrum, the maximum effect being caused by the yellow rays, while anabolic or constructive changes occur when no light at all falls upon the retina. The chemical changes of this substance correspond, therefore, to the sensation of luminosity as distinguished from color. In a second substance red rays are supposed to produce katabolic, and green rays anabolic changes, while a third substance is similarly affected by yellow and blue rays. These two substances are therefore spoken of as red-green and yellow-blue visual substances respectively.

It has been sometimes urged as an objection to this theory that the effect of a stimulus is usually katabolic and not anabolic. This is true with regard to muscular contraction, from the study of which phenomenon most of our knowledge of the effect of stimulation has been obtained, but it should be remem-

bered that observations on the augmentor and inhibitory cardiac nerves have shown us that nerve-stimulation may produce very contrary effects. There seems to be, therefore, no serious theoretical difficulty in supposing that light rays of different wave-lengths may produce opposite metabolic effects upon the substances in which changes are associated with visual sensations.

A more serious objection lies in the difficulty of distinguishing between the sensation of blackness, which, on Hering's hypothesis, must correspond to active anabolism of the white-black substance, and the sensation of darkness (such as we experience when the eyes have been withdrawn for some time from the influence of light), which must correspond to a condition of equilibrium of the white-black substance in which neither anabolism nor katabolism is occurring.

Another objection to the Hering theory is to be found in the results of experiments in comparing grays or whites produced by mixing different colored rays under varying intensities of light. The explanation given by Hering of the production of white through the mixture of blue and yellow or of red and green is that when either of these pairs of complementary colors is mixed the anabolic and the katabolic processes balance each other, leaving the corresponding visual substance in a condition of equilibrium. Hence, the white-black substance being alone stimulated, the result will be a sensation of white corresponding to the intensity of the katabolic process caused by the mixed rays. Now, it is found that when blue and yellow are mixed in certain proportions on a revolving disk a white can be produced which will, with a certain intensity of illumination, be undistinguishable from a white produced by mixing red and green. If, however, the intensity of the illumination is changed, it will be found necessary to add a certain amount of white to one of the mixtures in order to bring them to equality. On the theory that complementary colors produce antagonistic processes in the retina it is difficult to understand why this should be the case.

A color theory which is in some respects more in harmony with recent observations in the physiology of vision has been proposed by Mrs. C. L. Franklin. In this theory it is supposed that, in its earlier periods of development, the eye is sensitive only to luminosity and not to color—*i. e.* it possesses only a white-black or (to use a single word) a *gray*-perceiving substance which is affected by all visible light rays, but most powerfully by those lying near the middle of the spectrum. The sensation of gray is supposed to be dependent upon the chemical stimulation of the optic nerve-terminations by some product of decomposition of this substance.

In the course of development a portion of this gray visual substance becomes differentiated into three different substances, each of which is affected by rays of light corresponding to one of the three fundamental colors of the spectrum —viz. red, green, and blue. When a ray of light intermediate between two of the fundamental colors falls upon the retina, the visual substances corresponding to these two colors will be affected to a degree proportionate to the proximity of these two colors to that of the incident ray. Since this effect is

exactly the same as that which is produced when the retina is acted upon simultaneously by light of two fundamental colors, we are incapable of distinguishing in sensation between an intermediate wave-length and a mixture in proper amounts of two fundamental wave-lengths.

When the retina is affected by two or more rays of such wave-lengths that all three of the color visual substances are equally affected, the resulting decomposition will be the same as that produced by the stimulation of the gray visual substance out of which the color visual substances were differentiated, and the corresponding sensation will therefore be that of gray or white.

It will be noticed that the important feature of this theory is that it provides for the independent existence of the gray visual substance, while at the same time the stimulation of this substance is made a necessary result of the mixture of certain color sensations.

Color-blindness.—The fact that many individuals are incapable of distinguishing between certain colors—*i. e.* are more or less "color-blind"—is one of fundamental importance in the discussion of theories of color vision. By far the most common kind of color-blindness is that in which certain shades of red and green are not recognized as different colors. The advocates of the Young-Helmholtz theory explain such cases by supposing that either the red or the green perceiving elements of the retina are deficient, or, if present, are irritable, not by rays of a particular wave-length, but by all the rays of the visible spectrum. In accordance with this view these cases of color-blindness are divided into two classes—viz. the red-blind and the green-blind—the basis for the classification being furnished by more or less characteristic curves representing the variations in the luminosity of the visible spectrum as it appears to the different eyes. There are, however, cases which cannot easily be brought under either of these two classes. Moreover, it has been proved in cases of monocular color-blindness, and is admitted even by the defenders of the Helmholtz theory, that such persons see really only two colors—viz. blue and yellow. To such persons the red end of the spectrum appears a dark yellow, and the green portion of the spectrum has luminosity without color.

A better explanation of this sort of color-blindness is given in the Hering theory by simply supposing that in such eyes the red-green visual substance is deficient or wholly wanting, but the theory of Mrs. Franklin accounts for the phenomena in a still more satisfactory way; for, by supposing that the differentiation of the primary gray visual substance has first led to the formation of a blue and a yellow visual substance, and that the latter has subsequently been differentiated into a red and a green visual substance, color-blindness is readily explained by supposing that this second differentiation has either not occurred at all or has taken place in an imperfect manner. It is, in other words, an arrest of development.

Cases of *absolute* color-blindness are said to occasionally occur. To such persons nature is colorless, all objects presenting simply differences of light and shade.

In whatever way color-blindness is to be explained, the defect is one of

considerable practical importance, since it renders those affected by it incapable of distinguishing the red and green lights ordinarily used for signals. Such persons are, therefore, unsuitable for employment as pilots, railway engineers, etc., and it is now customary to test the vision of all candidates for employment in such situations. It has been found that no satisfactory results can be reached by requiring persons to name colors which are shown them, and the chromatic sense is now commonly tested by what is known as the "Holmgren method," which consists in requiring the individual examined to select from a pile of worsteds of various colors those shades which seem to him to resemble standard skeins of green and pink. When examined in this way about 4 per cent. of the male and one-quarter of 1 per cent. of the female sex are found to be more or less color-blind. The defect may be inherited, and the relatives of a color-blind person are therefore to be tested with special care. Since females are less liable to be affected than males, it often happens that the daughters of a color-blind person, themselves with normal vision, have sons who inherit their grandfather's infirmity.

Although in all theories of color vision the different sensations are supposed to depend upon changes produced by the ether vibrations of varying rates acting upon different substances in the retina, yet it should be borne in mind that we have at present no proof of the existence of any such substances. The visual purple—or, to adopt Mrs. Franklin's more appropriate term, "the rod pigment"—was at one time thought to be such a substance, but for the reasons above given cannot be regarded as essential to vision.[1]

That a centre for color vision, distinct from the visual centre, exists in the cerebral cortex is rendered probable by the occurrence of cases of hemianopsia for colors, and also by the experiments of Heidenhain and Cohn on the influence of the hypnotic trance upon color-blindness.

Intensity.—The second of the above-mentioned qualitative modifications of light is its intensity, which is dependent upon the energy of vibrations of the molecules of the luminiferous ether. The sensation of luminosity is not, however, proportionate to the intensity of the stimulus, but varies in such a way that a given *increment* of intensity causes a greater difference in sensation with feeble than with strong illuminations. This phenomenon is illustrated by the disappearance of a shadow thrown by a candle in a darkened room on a sheet of white paper when sunlight is allowed to fall on the paper from the opposite direction. In this case the absolute difference in luminosity between the shadowed and unshadowed portions of the paper remains the same, but it becomes imperceptible in consequence of the increased total illumination.

Although our power of distinguishing *absolute* differences in luminosity diminishes as the intensity of the illumination increases, yet with regard to *relative* differences no such dependence exists. On the contrary, it is found within pretty wide limits that, whatever be the intensity of the illumination,

[1] In a recently developed theory by Ebbinghaus (*Zeitschrift für Psychologie und Physiologie der Sinnesorgane*, v. 145) a physiological importance in relation to vision is attached to this substance in connection with other substances of a hypothetical character.

it must be increased by a certain constant fraction of its total amount in order to produce a perceptible difference in sensation. This is only a special case of a general law of sensation known as Weber's law, which has been formulated by Foster as follows: "The smallest change in the magnitude of a stimulus which we can appreciate through a change in our sensation always bears the same proportion to the whole magnitude of the stimulus."

Luminosity of Different Colors.—When two sources of light having the same color are compared, it is possible to estimate their relative luminosity with considerable accuracy, a difference of about 1 per cent. of the total luminosity being appreciated by the eye. When the sources of light have different colors, much less accuracy is attainable, but there is still a great difference in the intensity with which rays of light of different wave-lengths affect the retina. We do not hesitate to say, for instance, that the maximum intensity of the solar spectrum is found in the yellow portion, but it is important to observe that the position of this maximum varies with the illumination. In a very brilliant spectrum the maximum shifts toward the orange, and in a feeble spectrum (such as may be obtained by narrowing the slit of the spectroscope) it moves toward the green. The curves in Figure 240 illus-

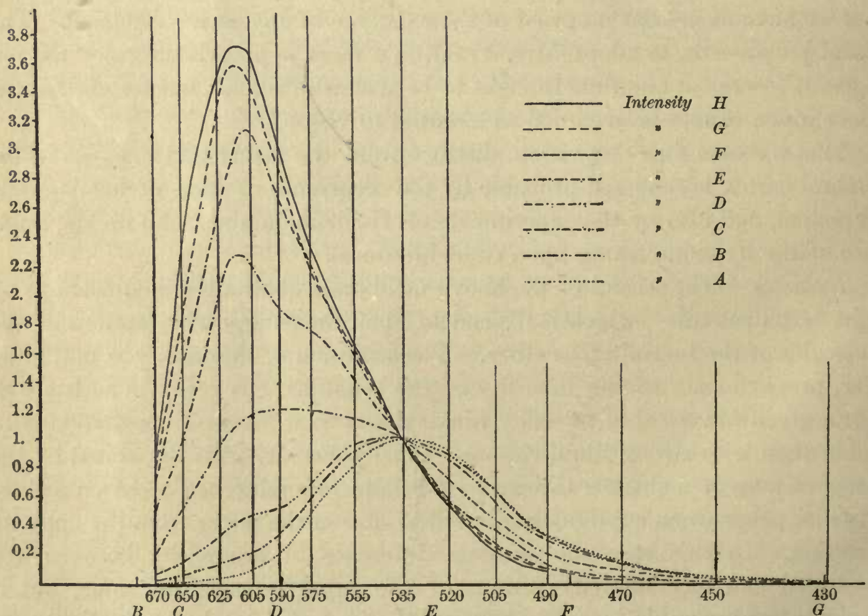


FIG. 240.—Diagram showing the distribution of the intensity of the spectrum as dependent upon the degree of illumination (König).

trate this shifting of the maximum of luminosity of the spectrum with varying intensities of illumination. The abscissas represent wave-lengths in millionths of a millimeter, and the ordinates the luminosity of the different colors as expressed by the reciprocal values of the width of the slit necessary to give to the color under observation a luminosity equal to that of an arbi-

trarily chosen standard. The curves from A to H represent the distribution of the intensity of light in the spectrum with eight different grades of illumination. This shifting of the maximum of luminosity in the spectrum explains the so-called "Purkinje's phenomenon"—viz. the changing relative values of colors in varying illumination. This can be best observed at nightfall, the attention being directed to a carpet or a wall-paper the pattern of which is made up of a number of different colors. As the daylight fades away the red colors, which in full illumination are the most intense, become gradually darker, and are scarcely to be distinguished from black at a time when the blue colors are still very readily distinguished.

Function of Rods and Cones.—The layer of rods and cones has thus far been spoken of as if all its elements had one and the same function. There is, however, some reason to suppose that the rods and cones have different functions. That color sensation and accuracy of definition are most perfect in the central portion of the retina is shown by the fact that when we desire to obtain the best possible idea of the form and color of an object we direct our eyes in such a way that the image falls upon the fovea centralis of the retina. The luminosity of a faint object, however, seems greatest when we look not directly at it, but a little to one side of it. This can be readily observed when we look at a group of stars, as, for example, the Pleiades. When the eyes are accurately directed to the stars so as to enable us to count them, the total luminosity of the constellation appears much less than when the eyes are directed to a point a few degrees to one side of the object. Now, an examination of the retina shows only cones in the fovea centralis. In the immediately adjacent parts a small number of rods are found mingled with the cones. In the lateral portions of the retina the rods are relatively more numerous than the cones, and in the extreme peripheral portions the rods alone exist. Hence this phenomenon is readily explained on the supposition that the rods are a comparatively rudimentary form of visual apparatus taking cognizance of the existence of light with special reference to its varying intensity, and that the cones are organs specially modified for the localization of stimuli and for the perception of differences of wave-lengths. The view that the rods are specially adapted for the perception of luminosity and the cones for that of color derives support from the fact that in the retina of certain nocturnal animals—*e. g.* bats and owls—rods alone are present. This theory has been further developed by Von Kries,[1] who in a recent article describes the rods as differing from the cones in the following respects: (1) They are color-blind—*i. e.* they produce a sensation of simple luminosity whatever be the wave-length of the light-ray falling on them; (2) they are more easily stimulated than the cones, and are particularly responsive to light-waves of short wave-lengths; (3) they have the power of adapting themselves to light of varying intensity.

On this theory it is evident that we must get the sensation of white or

[1] *Zeitschrift für Psychologie und Physiologie der Sinnesorgane*, ix. 81.

colorless light in two different ways: (1) In consequence of the stimulation of the rods by any sort of light-rays, and (2) in consequence of the stimulation of the cones by certain combinations of light-rays—*i. e.* complementary colors. In this double mode of white perception lies perhaps the explanation of the effect of varying intensity of illumination upon the results of color-mixtures which has been above alluded to (see p. 783) as an objection to the Hering theory. The so-called "Purkinje's phenomenon," described on p. 787, is readily explained in accordance with this theory, for, owing to the greater irritability of the rods, the importance of these organs, as compared with the cones, in the production of the total visual sensation is greater with feeble than with strong illumination of the field of vision. At the same time, the power of the rods to respond particularly to light-rays of short wave-length will cause a greater apparent intensity of the colors at the blue than at the red end of the spectrum. In this connection it is interesting to note that the phenomenon is said not to occur when the observation is limited to the fovea centralis, where cones alone are found.[1]

Saturation.—The degree of saturation of light of a given color depends, as above stated, upon the amount of white light mixed with it. The quality of light thus designated is best studied and appreciated by means of experiments with rotating disks. If, for instance, a disk consisting of a large white and a small red sector be rapidly rotated, the effect produced is that of a pale pink color. By gradually increasing the relative size of the red sector the pink color becomes more and more saturated, and finally when the white sector is reduced to zero the maximum of saturation is produced. It must be borne in mind, however, that no pigments represent completely saturated colors. Even the colors of the spectrum do not produce a sensation of absolute saturation, for, whatever theory of color vision be adopted, it is evident that all the color-perceiving elements of the retina are affected *more or less* by all the rays of light. Thus when rays of red light fall upon the retina they will stimulate not only the red-perceiving elements, but to a slight extent also (to use the language of the Helmholtz theory) the green- and violet-perceiving elements of the retina. The effect of this will be that of mixing a small amount of white with a large amount of red light—*i. e.* it will produce the sensation of incompletely saturated red light. This dilution of the sensation can be avoided only by previously exhausting the blue- and green-perceiving elements of the retina in a manner which will be explained in connection with the phenomena of after-images.

Retinal Stimulation.—Whenever by a stimulus applied to an irritable substance the potential energy there stored up is liberated the following phenomena may be observed: 1. A so-called latent period of variable duration during which no effects of stimulation are manifest; 2. A very brief period during which the effect of the stimulation reaches a maximum; 3. A period of continued stimulation during which the effect diminishes in consequence of the using up of the substance containing the potential energy—*i. e.* a period

[1] Von Kries: *Centralblatt für Physiologie*, 1896, i.

of fatigue; 4. A period after the stimulation has ceased in which the effect slowly passes away.

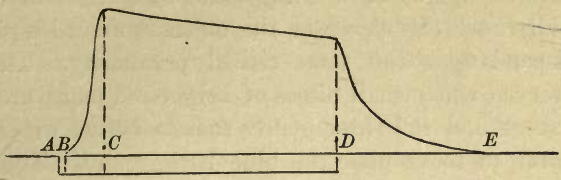
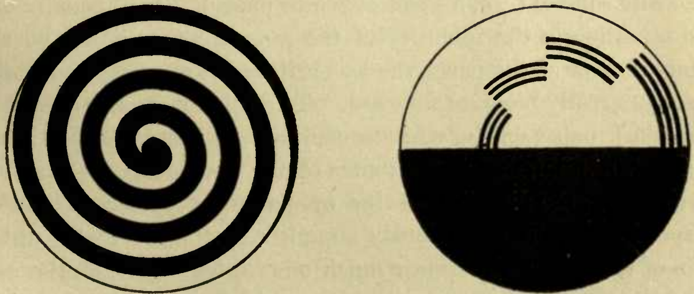


Fig. 241.—Diagram showing the effect of stimulation of an irritable substance.

The curve drawn by a muscle in tetanic contraction, as shown in Figure 241, illustrates this phenomenon. Thus, if *A D* represents the duration of the stimulation, *A B* indicates the latent period, *B C* the period of contraction, *C D* the period of fatigue under stimulation, and *D E* the after-effect of stimulation showing itself as a slow relaxation. When light falls upon the retina corresponding phenomena are to be observed.

Latent Period.—That there is a period of latent sensation in the retina (*i. e.* an interval between the falling of light on the retina and the beginning of the sensation) is, judging from the analogy of other parts of the nervous system, quite probable, though its existence has not been demonstrated.

Rise to Maximum of Sensation.—The rapidity with which the sensation of light reaches its maximum increases with the intensity of the light and varies with its color, red light producing its maximum sensation sooner than green and blue. Consequently, when the image of a white object is moved across the retina it will appear bordered by colored fringes, since the various constituents of white light do not produce their maximum effects at the same time. This phenomena can be readily observed when a disk on which a black and a white spiral band alternate with each other (as shown in Figure 242, *A*) is rotated before the eyes. The white band as its image moves out-



A *B*

Fig. 242.—Disks to illustrate the varying rate at which colors rise to their maximum of sensation.

ward or inward over the retinal surface appears bordered with colors which vary with the rate of rotation of the disk and with the amount of exhaustion of the retina. Chromatic effects due to a similar cause are also to be seen when a disk, such as is shown in Figure 242, *B* (known as Benham's spectrum

top), is rotated with moderate rapidity. The concentric bands of color appear in reverse order when the direction of rotation is reversed. The apparent movement of colored figures on a background of a different color when the eye moves rapidly over the object or the object is moved rapidly before the eye seems to depend upon this same retinal peculiarity. The phenomenon may be best observed when small pieces of bright-red paper are fastened upon a bright-blue sheet and the sheet gently shaken before the eyes. The red figures will appear to move upon the blue background. The effect may be best observed in a dimly-lighted room.

In this connection should be mentioned the phenomenon of "recurrent images" or "oscillatory activity of the retina."[1] This may be best observed when a black disk containing a white sector is rotated at a rate of about one revolution in two seconds. If the disk is brightly illuminated, as by sunlight, and the eye fixed steadily upon the axis of rotation, the moving white sector seems to have a shadow upon it a short distance behind its advancing border, and this shadow may be followed by a second fainter, and even by a third still fainter shadow, as shown in Figure 243. The distance of the shadows from each other and from the edge of the sector increases with the rate of rotation of the disk and corresponds to a time interval of about 0.015″. It thus appears that when light is suddenly thrown upon the retina the sensation does not at once rise to its maximum, but reaches this point by a sort of vibratory movement. The apparent duplication of a single very brief retinal stimulation, as that caused by a flash of lightning, may perhaps be a phenomenon of the same sort.

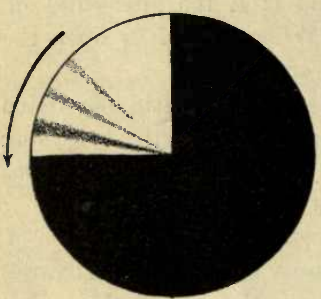


FIG. 243.—To illustrate the oscillatory activity of the retina (Charpentier).

Fatigue of Retina.—When the eye rests steadily upon a uniformly illuminated white surface (*e. g.* a sheet of white paper), we are usually unconscious of any diminution in the intensity of the sensation, but it can be shown that the longer we look at the paper the less brilliant it appears, or, in other words, that the retina really becomes fatigued. To do this it is only necessary to place a disk of black paper on the white surface and to keep the eyes steadily fixed for about half a minute upon the centre of the disk. Upon removing the disk without changing the direction of the eyes a round spot will be seen on the white paper in the place previously occupied by the disk. On this spot the whiteness of the paper will appear much more intense than on the neighboring portion of the sheet, because we are able in this experiment to bring into direct contrast the sensations produced by a given amount of light upon a fresh and a fatigued portion of the retina.[2]

[1] Charpentier: *Archives de Physiologie*, 1892, pp. 541, 629; and 1896, p. 677.

[2] Although the retina is here spoken of as the portion of the visual apparatus subject to fatigue, it should be borne in mind that we cannot, in the present state of our knowledge, discriminate between retinal fatigue and exhaustion of the visual nerve-centres.

The rapidity with which the retina becomes fatigued varies with the color of the light. Hence when intense white light falls upon the retina, as when we look at the setting sun, its disk seems to undergo changes of color as one or another of the constituents of its light becomes, through fatigue, less and less conspicuous in the combination of rays which produces the sensation of white.

The After-effect of Stimulation.—The persistence of the sensation after the stimulus has ceased causes very brief illuminations (*e. g.* by an electric spark) to produce distinct effects. On this phenomenon depends also the above-described method of mixing colors on a revolving disk, since a second color is thrown upon the retina before the impression produced by the first color has had time enough to become sensibly diminished. The interval at which successive stimulations must follow each other in order to produce a uniform sensation (a process analogous to the tetanic stimulation of a muscle) may be determined by rotating a disk, such as represented in Figure 244, and ascertaining at what speed the various rings produce a uniform sensation of gray. The interval varies with the intensity of the illumination from 0.1″ to 0.033″. The duration of the after-effect depends also upon the length of the stimulation and upon the color of the light producing it, the most persistent effect being produced by the red rays. In this connection it is interesting to note that while with the rapidly vibrating blue rays a less intense illumination suffices to stimulate the eye, the slowly vibrating red rays produce the more permanent impression.

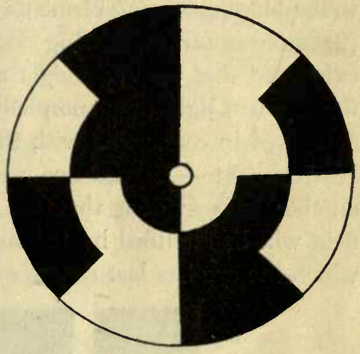


FIG. 244.—Disk to illustrate the persistence of retinal sensation (Helmholtz).

After-images.—When the object looked at is very brightly illuminated the impression upon the retina may be so persistent that the form and color of the object are distinctly visible for a considerable time after the stimulus has ceased to act. This appearance is known as a " positive after-image," and can be best observed when we close the eyes after looking at the sun or other bright source of light. Under these circumstances we perceive a brilliant spot of light which, owing to the above-mentioned difference in the persistence of the impressions produced by the various colored rays, rapidly changes its color, passing generally through bluish green, blue, violet, purple, and red, and then disappearing. This phenomenon is apt to be associated with or followed by another effect known as a " negative after-image." This form of after-image is much more readily observed than the positive variety, and seems to depend upon the fatigue of the retina. It is distinguished from the positive after-image by the fact that its color is always complementary to that of the object causing it. In the experiment to demonstrate the fatigue of the retina, described on p. 790, the white spot which appears after the black disk is withdrawn is the " negative after-image" of the disk, white being complementary to black. If a

colored disk be placed upon a sheet of white paper, looked at attentively for a few seconds, and then withdrawn, the eye will perceive in its place a spot of light of a color complementary to that of the disk. If, for example, the disk be yellow, the yellow-perceiving elements of the retina become fatigued in looking at it. Therefore when the mixed rays constituting white light are thrown upon the portion of the retina which is thus fatigued, those rays which produce the sensation of yellow will produce less effect than the other rays for which the eye has not been fatigued. Hence white light to an eye fatigued for yellow will appear blue.

If the experiment be made with a yellow disk resting on a sheet of blue paper, the negative after-image will be a spot on which the blue color will appear (1) more *intense* than on the neighboring portions of the sheet, owing to the blue-perceiving elements of that portion of the retina not being fatigued; (2) more *saturated*, owing to the yellow-perceiving elements being so far exhausted that they no longer respond to the slight stimulation which is produced when light of a complementary color is thrown upon them, as has been explained in connection with the subject of saturation.

Contrast.—As the eye wanders from one part of the field of vision to another it is evident that the sensation produced by a given portion of the field will be modified by the amount of fatigue produced by that portion on which the eye has last rested, or, other words, the sensation will be the result

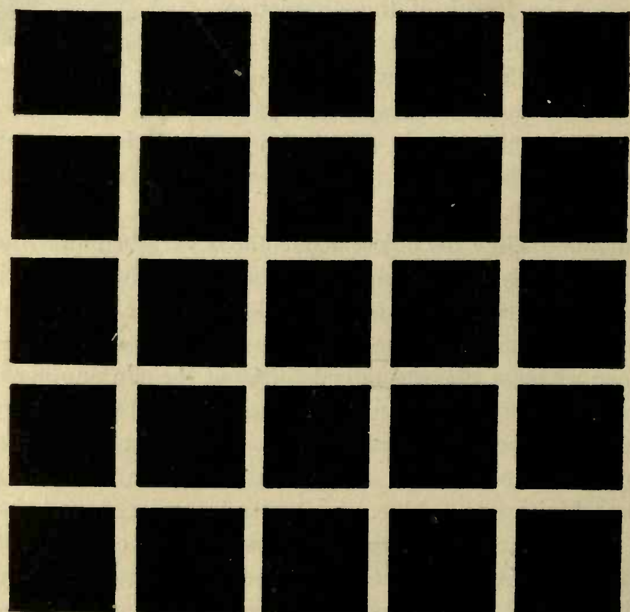


FIG. 245.—To illustrate the phenomenon of contrast.

of the stimulation by the object looked at combined with the negative after-image of the object previously observed. The effect of this combination is to produce the phenomenon of successive *contrast*, the principle of which may be thus stated: Every part of the field of vision appears lighter near a darker

part and darker near a lighter part, and its color seen near another color approaches the complementary color of the latter. A contrast phenomenon similar in its effects to that above described may be produced under conditions in which negative after-images can play no part. This kind of contrast is known as *simultaneous contrast*, and may perhaps be explained on the theory that a stimulation of a given portion of the retina produces in the neighboring portions an effect to some extent antagonistic to that caused by direct stimulation.

A good illustration of the phenomenon of contrast is given in Figure 245, in which black squares are separated by white bands which at their points of intersection appear darker than where they are bordered on either side by the black squares.

A black disk on a yellow background seen through white tissue-paper appears blue, since the white paper makes the black disk look gray and the yellow background pale yellow. The gray disk in contrast to the pale yellow around it appears blue.

The phenomenon of *colored shadows* also illustrates the principle of contrast. These may be observed whenever an object of suitable size and shape is placed upon a sheet of white paper and illuminated from one direction by daylight and from another by gaslight. Two shadows will be produced, one of which will appear yellow, since it is illuminated only by the yellowish gas-light, while the other, though illuminated by the white light of day, will appear blue in contrast to the yellowish light around it.

Space-perception.—Rays of light proceeding from every point in the field of vision are refracted to and stimulate a definite point on the surface of the retina, thus furnishing us with a local sign by which we can recognize the position of the point from which the light proceeds. Hence the size and shape of an optical image upon the retina enable us to judge of the size of the corresponding object in the same way that the cutaneous terminations of the nerves of touch enable us to judge of the size and shape of an object brought in contact with the skin. This spatial perception is materially aided by the muscular sense of the muscles moving the eyeball, for we can obtain a much more accurate idea of the size of an object if we let the eye rest in succession upon its different parts than if we gaze fixedly at a given point upon its surface. The conscious effort associated with a given amount of muscular motion gives, in the case of the eye, a measure of distance similar to that secured by the hand when we move the fingers over the surface of an object to obtain an idea of its size and shape.

The perception of space by the retina is limited to space in two dimensions —*i. e.* in a plane perpendicular to the axis of vision. Of the third dimension in space—*i. e.* of distance from the eye—the retinal image gives us no knowledge, as may be proved by the study of after-images. If an after-image of any bright object—*e. g.* a window—be produced upon the retina in the manner above described and the eye be then directed to a sheet of paper held in the hand, the object will appear outlined in miniature upon the surface of the paper. If, however, the eye be directed to the ceiling of the room, the object

will appear enlarged and at a distance corresponding to that of the surface looked at. Hence one and the same retinal image may, under different circumstances, give rise to the impression of objects at different distances. We must therefore regard the perception of distance not as a direct datum of vision, but, as will be later explained, a matter of visual judgment.

When objects are of such a shape that their images may be thrown successively upon the same part of the retina, it is possible to judge of their relative size with considerable accuracy, the retinal surface serving as a scale to which the images are successively applied. When this is not the case, the error of judgment is much greater. We can compare, for instance, the relative length of two vertical or of two horizontal lines with a good deal of precision, but in comparing a vertical with a horizontal line we are liable to make a considerable error. Thus it is difficult to realize that the vertical and the horizontal lines in Figure 246 are of the same length. The error consists in an over-estimation of the length of the vertical lines relatively to horizontal ones, and appears to depend, in part at any rate, upon the small size of the superior rectus muscle relatively to the other muscles of the eye. The difference amounts to 30–45 per cent. in weight and 40–53 per cent. in area of cross section. It is evident, therefore, that a given motion of the eye in the upward direction will require a more powerful contraction of the weaker muscle concerned in the movement than will be demanded of the stronger muscles moving the eye laterally to an equal amount. Hence we judge the upward motion of the eye to be greater because to accomplish it we make a greater effort than is required for a horizontal movement of equal extent.

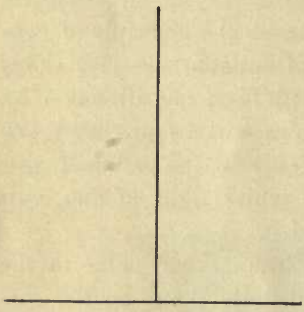


FIG. 246.—To illustrate the over-estimation of vertical lines.

The position of the vertical line bisecting the horizontal one (in Fig. 246) aids the illusion, as may be seen by turning the page through 90°, so as to bring the bisected line into a vertical position, or by looking at the lines in Figure 247, in which the illusion is much less marked than in Figure 246.

The tendency to over-estimate the length of vertical lines is also illustrated by the error commonly made in supposing the height of the crown of an ordinary silk hat to be greater than its breadth.

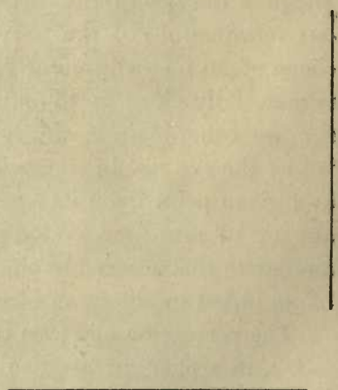


FIG. 247.—To illustrate the over-estimation of vertical lines.

Irradiation.—Many other circumstances affect the accuracy of the spatial perception of the retina. One of the most important of these is the intensity of the illumination. All brilliantly illuminated objects appear larger than feebly illuminated ones of the same size, as is

well shown by the ordinary incandescent electric lamp, the delicate filament of which is scarcely visible when cold, but when intensely heated by the electric current glows as a broad band of light. The phenomenon is known as "irradiation," and seems to depend chiefly upon the above-described imperfections in the dioptric apparatus of the eye, in consequence of which points of light produce small circles of dispersion on the retina and bright objects produce

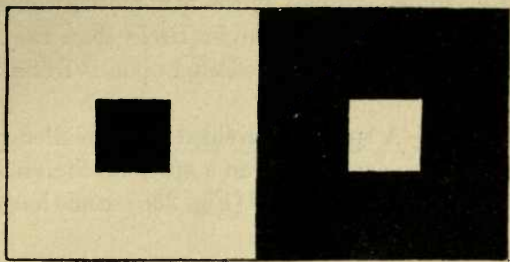


FIG. 248.—To illustrate the phenomenon of irradiation.

images with imperfectly defined outlines. The white square surrounded by black and the black square surrounded by white (Figure 248), being of the same size, would in an ideally perfect eye produce images of the same size on the retina, but owing to the imperfections of the eye the images are not sharply

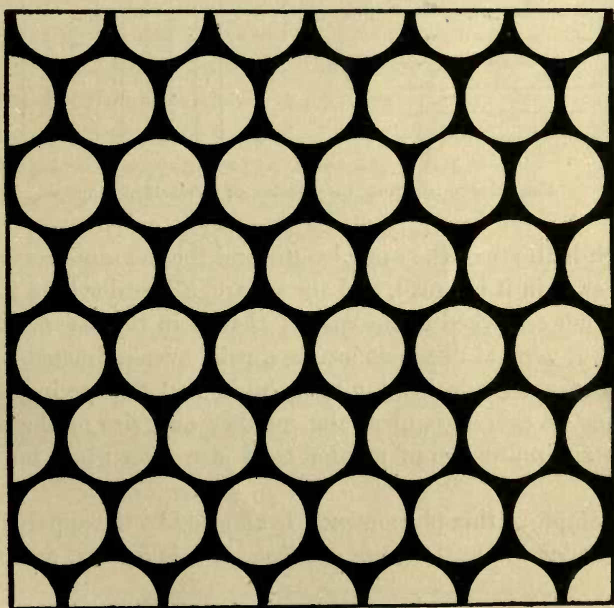


FIG. 249.—To illustrate the phenomenon of irradiation.

defined, and the white surfaces consequently appear to encroach upon the darker portions of the field of vision. Hence the white square looks larger than the black one, the difference in the apparent size depending upon the intensity of the illumination and upon the accuracy with which the eye can be accommo-

dated for the distance at which the objects are viewed. The effect of irradiation is most manifest when the dark portion of the field of vision over which the irradiation takes place has a considerable breadth. Thus the circular white spots in Figure 249, when viewed from a distance of three or four meters, appear hexagonal, since the irradiation is most marked into the triangular dark space between three adjacent circles. A familiar example of the effect of irradiation is afforded by the appearance of the new moon, whose sun-illuminated crescent seems to be part of a much larger circle than the remainder of the disk, which shines only by the light reflected upon it from the surface of the earth.

Subdivided Space.—A space subdivided into smaller portions by intermediate objects seems more extensive than a space of the same size not so subdivided. Thus the distance from *A* to *B* (Fig. 250) seems longer than that from

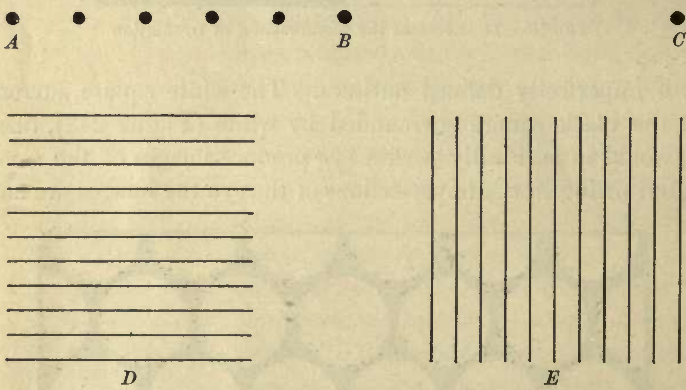


FIG. 250.—To illustrate the illusion of subdivided space.

B to *C*, though both are of the same length, and for the same reason the square *D* seems higher than it is broad, and the square *E* broader than it is high, the illusion being more marked in the case of *D* than in the case of *E*, because, as above explained, vertical distances are, as a rule, over-estimated.

The explanation of this illusion seems to be that the eye in passing over a subdivided line or area recognizes the number and size of the subdivisions, and thus gets an impression of greater total size than when no subdivisions are present.

A good example of this phenomenon is afforded by the apparently increased extent of a meadow when the grass growing on it is cut and arranged in haycocks.[1]

The relations of lines to each other gives rise to numerous illusions of spatial perception, among the most striking of which are those afforded by the so-called "Zöllner's lines," an example of which is given in Figure 251. Here

[1] It is interesting to note that a similar illusion has been observed when an interval of time subdivided by audible signals is compared with an equal interval not so subdivided (Hall and Jastrow: *Mind*, xi. 62).

the horizontal lines, though strictly parallel to each other, seem to diverge and converge alternately, their apparent direction being changed toward greater per-

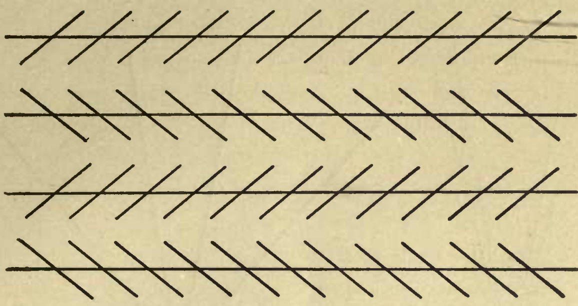


FIG. 251.—Zöllner's lines.

pendicularity to the short oblique lines crossing them. This illusion is to be explained in part by the tendency of the eye to over-estimate the size of acute and to under-estimate that of obtuse angles—a tendency which also affords a partial explanation of the illusion in Figure 252, where the line *d* is the real and the line *f* the apparent continuation of the line *a*. The illusion in Zöllner's figures is more marked when the figure is so held that the long parallel lines make an angle of about 45° with the horizon, since in this position the eye appreciates their real position less accurately than when they are vertical or horizontal. It is diminished, but does not disappear, when the eye, instead of being allowed to wander over the figure, is fixed upon any one point of the field of vision. Hence the motions of the eye must be regarded as a factor in, but not the sole cause of, the illusion.

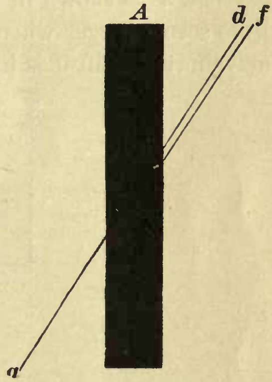


FIG. 252.—To illustrate illusion of space-perception.

Our estimate of the size of given lines, angles, and areas is influenced by neighboring lines, angles, and areas with which they are compared. This influence is sometimes exerted in accordance with the principle of contrast, and tends to make a given extension appear larger in presence of a smaller,

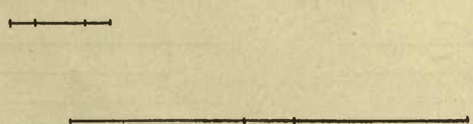


FIG. 253.—To illustrate contrast in space-perception (Müller-Lyer).

and smaller in presence of a larger extension. This effect is illustrated in Figure 253, in which the middle portion of the shorter line appears larger than the corresponding portion of the longer line, in Figure 254, in which a similar effect is observed in the case of angles, and in Figure 255, in which

the space between the two squares seems smaller than that between the two oblong figures.

In some case, however, an influence of the opposite sort[1] seems to be

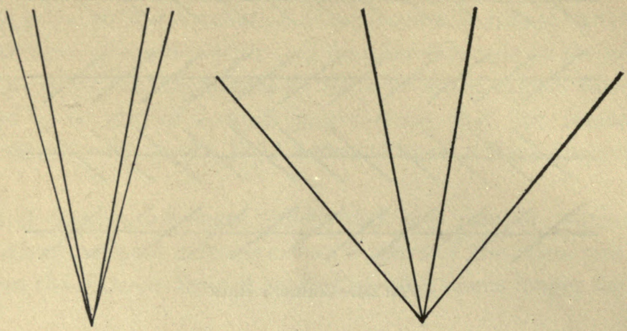


FIG. 254.—To illustrate contrast in space-perception (Müller-Lyer).

exerted, as is shown in Figure 256, in which the middle one of three parallel lines seems longer when the outside lines are longer, and shorter when they are shorter than it is itself, and in Figure 257, where a circle appears larger

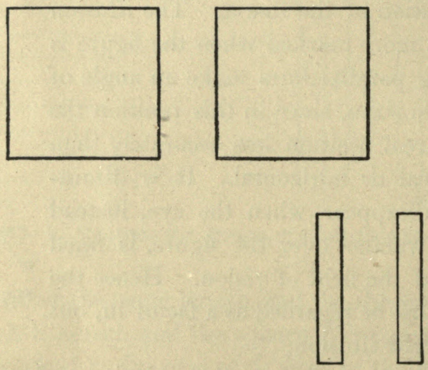


FIG. 255.—To illustrate contrast in space-perception (Müller-Lyer).

if surrounded by a circle larger than itself, and smaller if a smaller circle is shown concentrically within it.

Lines meeting at an angle appear longer when the included angle is large

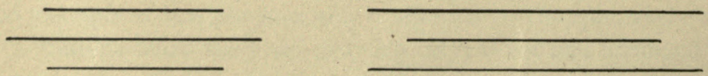


FIG. 256.—To illustrate so-called "confluxion" in space-perception (Müller-Lyer).

than when it is small, as is shown in Figure 258. This influence of the included angle affords a partial explanation of the illusion shown in Figure 259, where the horizontal line at *B* seems longer than at *A*; but the distance

[1] For this influence the name "confluxion" has been proposed by Müller-Lyer, from whose article in the *Archiv für Physiologie*, 1889, Sup. Bd., the above examples are taken.

between the extremities of the oblique lines seems also to affect our estimate of the horizontal line in the same way as the outside lines in Figure 256 influence our judgment of the length of the line between them.

Perception of Distance.—The retinal image gives us, as we have seen, no *direct* information as to the distance of the object from the eye. This

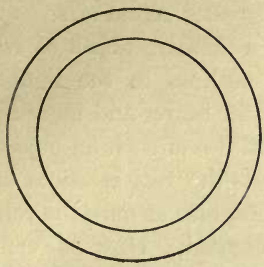


FIG. 257.—To illustrate so-called "confluxion" in space-perception (Müller-Lyer).

knowledge is, however, quite as important as that of position in a plane perpendicular to the line of vision, and we must now consider in what way it is obtained. The first fact to be noted is that there is a close connection between the judgments of distance and of actual size. A retinal image of a given size may be produced by a small object near the eye or by a large one at a

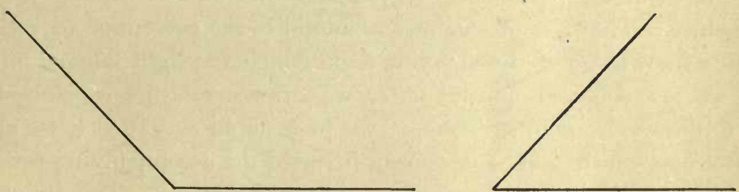


FIG. 258.—To illustrate the influence of angles upon the apparent length of lines (Müller-Lyer).

distance from it. Hence when we know the actual size of any object (as, for example, a human figure) we judge of its distance by the size of its image on the retina. Conversely, our estimate of the actual size of an object will depend upon our judgment of its distance. The fact that children constantly misjudge both the size and distance of objects shows that the knowledge of

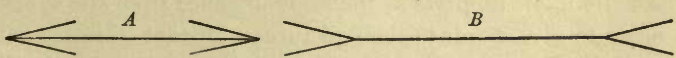


FIG. 259.—Illusion of space-perception.

this relation is acquired only by experience. If circumstances mislead us with regard to the distance of an object, we necessarily make a corresponding error with regard to its size. Thus, objects seen indistinctly, as through a fog, are judged to be larger, because we suppose them to be farther off, than they really are. The familiar fact that the moon seems to be larger when near the horizon than when near the zenith is also an illustration of this form of illu-

sion. When the moon is high above our heads we have no means of estimating its distance from us, since there are no intervening objects with which we can compare it. Hence we judge it to be nearer than when, seen on the horizon, it is obviously farther off than all terrestrial objects. Since the size of the retinal image of the moon is the same in the two cases, we reconcile the sensation with its apparent greater distance when seen on the horizon by attributing to the moon in this position a greater actual size.

If the retinal image have the form of a familiar object of regular shape—*e. g.* a house or a table—we interpret its outlines in the light of experience and distinguish without difficulty between the nearer and more remote parts of the object. Even the projection of the outlines of such an object on to a plane surface (*i. e.* a perspective drawing) suggests the real relations of the different parts of the picture so strongly that we recognize at once the relative distances of the various portions of the object represented. How powerfully a familiar outline can suggest the form and relief usually associated with it is well illustrated by the experiment of looking into a mask painted on its *interior* to resemble a human face. In this case the familiar outlines of a human face are brought into unfamiliar association with a receding instead of a projecting form, but the ordinary association of these outlines is strong enough to force the eye to see the hollow mask as a projecting face.[1] The fact that the projecting portions of an object are usually more brightly illuminated than the receding or depressed portions is of great assistance in determining their relative distance. This use of shadows as an aid to the perception of relief presupposes a knowledge of the direction from which the light falls on an object, and if we are deceived on the latter we draw erroneous conclusions with regard to the former point. Thus, if we look at an embossed letter or figure through a lens which makes it appear inverted the accompanying reversal of the shadows will cause the letter to appear depressed. The influence of shadows on our judgment of relief is, however, not so strong as that of the outline of a familiar object. In a case of conflicting testimony the latter usually prevails, as, for example, in the above-mentioned experiment with the mask.

Aided by these peculiarities of the retinal picture, the mind interprets it as corresponding in its different parts to points at different distances from the eye, and it is interesting to notice that painters, whose work, being on a plane surface, is necessarily in all its parts at the same distance from the eye, use similar devices in order to give depth to their pictures. Distant hills are painted with indistinct outlines to secure what is called "aërial perspective." Figures of men and animals are introduced in appropriate dimensions to suggest the distance between the foreground and the background of the picture. Landscapes are painted preferably by morning and evening light, since at these hours the marked shadows aid materially in the suggestion of distance.

[1] In the experiment the mask should be placed at a distance of about two meters and one eye closed. Even with both eyes open the illusion often persists if the distance is increased to five or six meters.

The eye, however, can aid itself in the perception of depth in ways which the painter has not at his disposal. By the sense of effort associated with the act of accommodation we are able to estimate roughly the relative distance of objects before us. This aid to our judgment can, of course, be employed only in the case of objects comparatively near the eye. Its effectiveness is greater for objects not far from the near-point of vision, and diminishes rapidly as the distance is increased, and disappears for distances more than two or three meters from the eye.

When the head is moved from side to side an apparent change in the relative position of objects at different distances is produced, and, as the extent of this change is inversely proportional to the distance of the objects, it serves as a measure of distance. This method of obtaining the "parallax" of objects by a motion of the head is often noticeable in persons whose vision in one eye is absent or defective.

Binocular Vision.—The same result which is secured by the comparison of retinal images seen successively from slightly different points of view is obtained by the comparison of the images formed simultaneously by any object in the *two eyes*. In binocular vision we obtain a much more accurate idea of the shape and distance of objects around us than is possible with monocular vision, as may be proved by trying to touch objects in our neighborhood with a crooked stick, first with both eyes open and then with one eye shut. Whenever we look at a near solid object with two eyes, the right eye sees farther round the object on the right side and the left eye farther round on the left. The mental comparison of these two slightly different images produces the perception of solidity or depth, since experience has taught us that those objects only which have depth or solidity can affect the eyes in this way. Conversely, if two drawings or photographs differing from each other in the same way that the two retinal images of a solid object differ from each other are presented, one to the right and the other to the left eye, the two images will become blended in the mind and the perception of solidity will result. Upon this fact depends the effect of the instrument known as the stereoscope, the slides of which are generally pairs of photographs of natural objects taken simultaneous-

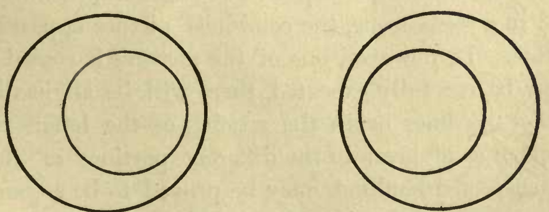


FIG. 260.—To illustrate stereoscopic vision.

ly with a double camera, of which the lenses are at a distance from each other equal to or slightly exceeding that between the two axes of vision. The principle of the stereoscope can be illustrated in a very simple manner by drawing circles such as are represented in Figure 260 on thin paper, and fastening each

pair across the end of a piece of brass tube about one inch or more in diameter and ten inches long. Let the tubes be held one in front of each eye with the distant ends nearly in contact with each other, as shown in Figure 261. If the tubes are in such a position that the small circles are brought as near to each other as possible, as shown in Figure 260, the retinal images will blend, the smaller circle will seem to be much nearer than the larger one, and the eyes will appear to be looking down upon a truncated cone, such as is shown in Figure 262, since a solid body of this form is the only one bounded by circles related to each other as those shown in this experiment.

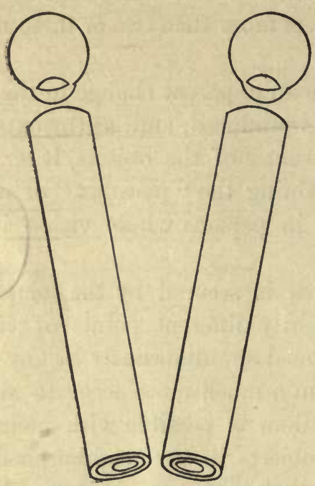


FIG. 261.—To illustrate stereoscopic vision.

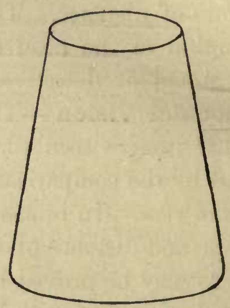


FIG. 262.—To illustrate stereoscopic vision.

Stereoscopic slides often serve well to illustrate the superiority of binocular over monocular vision. If the slide represents an irregular mass of rocks or ice, it is often very difficult by looking at either of the pictures by itself to determine the relative distance of the various objects represented, but if the slide is placed in the stereoscope the true relation of the different parts of the picture becomes at once apparent.

Since the comparison of two slightly dissimilar images received on the two retinas is the essential condition of stereoscopic vision, it is evident that if the two pictures are identical no sensation of relief can be produced. Thus, when two pages printed from the same type or two engravings printed from the same plate are united in a stereoscope, the combined picture appears as flat as either of its components. If, however, one of the pictures is copied from the other, even if the copy be carefully executed, there will be slight differences in the distances between the lines or in the spacing of the letters which will cause apparent irregularities of level in the different portions of the combined picture. Thus, a suspected banknote may be proved to be a counterfeit if, when placed in a stereoscope by the side of a genuine note, the resulting combined picture shows certain letters lying apparently on different planes from the rest.

Pseudoscopic Vision.—If the pictures of an ordinary stereoscopic slide be reversed, so that the picture belonging in front of the right eye is presented to the left eye, and *vice versâ*, the stereoscopic gives place to what is called a pseudoscopic effect—*i. e.* we perceive not a solid but a hollow body. The effect is best

obtained with the outlines of geometrical solids, photographs of coins or medals or of objects which may readily exist in an inverted form. Where the photographs represent objects which cannot be thus inverted, such as buildings and landscapes, the pseudoscopic effect is not readily produced—another example of the power (see p. 800) of the outline of a familiar object to outweigh other sorts of testimony.

A pseudoscopic effect may be readily obtained without the use of a stereoscope by simply converging the visual axes so that the right eye looks at the left and the left eye at the right picture of a stereoscopic slide. The eyes may be aided in assuming the right degree of convergence by looking at a small object like the head of a pin held between the eyes and the slide in the manner described on p. 758. Figure 260, viewed in this way, will present the appearance of a hollow truncated cone with the base turned toward the observer. A stereoscopic slide with its pictures reversed will, of course, when viewed in this way, present not a pseudoscopic, but a true stereoscopic, appearance, as shown by Figures 226 and 227.

Binocular Combination of Colors.—The effect of binocularly combining two different colors varies with the difference in wave-length of the colors. Colors lying near each other in the spectrum will generally blend together and produce the sensation of a mixed color, such as would result from the union of colors by means of the revolving disk or by the method of reflected and transmitted light, as above described. Thus a red and a yellow disk placed in a stereoscope may be generally combined to produce the sensation of orange. If, however, the colors are complementary to each other, as blue and yellow, no such mixing occurs, but the field of vision seems to be occupied alternately by a blue and by a yellow color. This so-called "rivalry of the fields of vision" seems to depend, to a certain extent, upon the fact that in order to see the different colors with equal distinctness the eyes must be differently accommodated, for it is found that if the colors are placed at different distances from the eyes (the colors with the less refrangible rays being at the greater distance), the rivalry tends to disappear and the mixed color is more easily produced.

An interesting effect of the stereoscopic combination of a black and a white object is the production of the appearance of a metallic lustre or polish. If, for instance, the two pictures of a stereoscopic slide represent the slightly different outlines of a geometrical solid, one in black upon white ground and the other in white upon black ground, their combination in the stereoscope will produce the effect of a solid body having a smooth lustrous surface. The explanation of this effect is to be found in the fact that a polished surface reflects the light differently to the two eyes, a given point appearing brilliantly illuminated to one eye and dark to the other. Hence the stereoscopic combination of black and white is interpreted as indicating a polished surface, since it is by means of a polished surface that this effect is usually produced.

Corresponding Points.—When the visual axes of both eyes are directed to the same object two distinct images of that object are formed upon widely

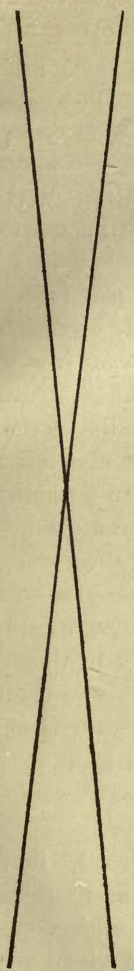
separated parts of the nervous system. Yet but a single object is perceived. The phenomenon is the same as that which occurs when a grain of sand is held between the thumb and finger. In both cases we have learned (chiefly through the agency of muscular movements and the nerves of muscular sense) to interpret the double sensation as produced by a single object.

Any two points, lying one in each retina, the stimulation of which by rays of light gives rise to the sensation of light proceeding from a single object are said to be "corresponding points." Now, it is evident that the *foveæ centrales* of the two eyes must be corresponding points, for an object always appears single when both eyes are fixed upon it. That double vision results when the images are formed on points which are not corresponding may be best illustrated by looking at three pins stuck in a straight rod at distances of 35, 45, and 55 centimeters from the end. If the end of the rod is held against the nose and the eyes directed to each of the three pins in succession, it will be found that, while the pin looked at appears single, each of the others appears double, and that the three pins therefore look like five.

The two *foveæ centrales* are not, of course, the only corresponding points. In fact, it may be said that the two retinas correspond to each other, point for point, almost as if they were superposed one upon the other with the foveæ together. The exact position of the points in space which are projected on to corresponding points of the two retinas varies with the position of the eyes. The line or surface in which such points lie is known as the "horopter." A full discussion of the horopter would be out of place in this connection, but one interesting result of its study may be pointed out—viz. the demonstration that when, standing upright, we direct our eyes to the horizon the horopter is approximately a plane coinciding with the ground on which we stand. It is of course important for security in walking that all objects on the ground should appear single, and, as they are known by experience to be single, the eye has apparently learned to see them so.

Since the vertical meridians of the two eyes represent approximately rows of corresponding points, it is evident that when two lines are so situated that their images are formed each upon a vertical meridian of one of the eyes, the impression of a single vertical line will be produced, for such a line seen binocularly is the most frequent cause of this sort of retinal stimulation. This is the explanation commonly given of the singular optical illusion which is produced when lines drawn as in Figure 263 are looked at with both eyes fixed upon the point of intersection of the lines and with the plane in which the visual axes lie forming an angle of about 20° with that of the paper, the distance of the lines from the eyes being such that each line will lie approximately in the same vertical plane with one of the visual axes. Under these circumstances each line will form its image on a vertical meridian of one of the eyes, and the combination of these images results in the perception of a third line, not lying in the plane of the paper, but apparently passing through it more or less vertically, and swinging round its middle point with every movement of the head or the paper. In this experiment it will be found that the illusion

of a line placed vertically to the plane of the paper does not entirely disappear when one eye is closed. Hence it is evident that there is, as Mrs.



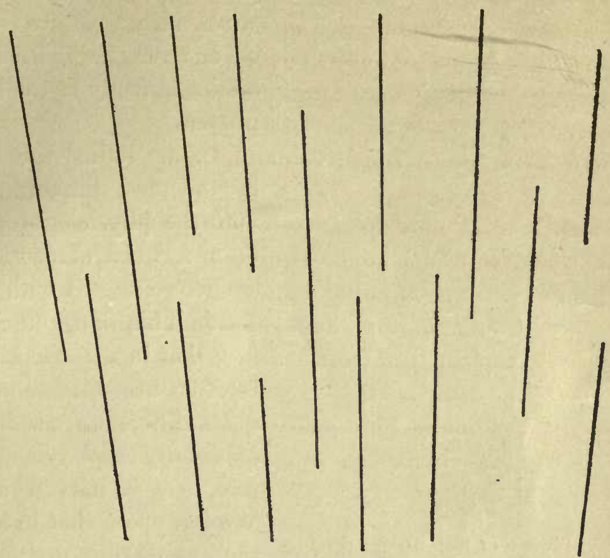


FIG. 264.—Monocular illusion of vertical lines.

C. L. Franklin has pointed out,[1] a strong tendency to regard lines which form their images approximately on the vertical meridian of the eye as themselves vertical. This tendency is well shown when a number of short lines converging toward a point outside of the paper on which they are drawn, as in Figure 264, are looked at with one eye held a short distance above the point of convergence. Even when the lines are not convergent, but parallel, so that their images cannot fall upon the vertical meridian of the eye, the illusion is not entirely lost. It will be found, for instance, that when the Zöllner lines, as given in Figure 251, are looked at obliquely with one eye from one corner of the figure, the short lines which lie nearly in a plane with the visual axis appear to stand vertically to the plane of the paper.

FIG. 263.—Binocular illusion of a vertical line.

In this connection it may be well to allude to the optical illusion in consequence of which certain portraits seem to follow the beholder with the eyes. This depends upon the fact that the face is painted looking straight out from the canvas —*i. e.* with the pupil in the middle of the eye. The painting being upon a flat surface, it is evident that, from whatever direction the picture is viewed, the pupil will always seem to be in the middle of the eye, and the eye will consequently appear to be directed upon the observer. The phenomenon is still more striking in the case of pictures of which the one represented in Figure 265 may be taken as an example. Here the soldier's rifle

[1] *Am. Journal of Psychology*, vol. i. p. 99.

is drawn as it appears to an eye looking straight down the barrel, and, as this foreshortening is the same in all positions of the observer, it is evident that when such a picture is hung upon the wall of a room the soldier will appear to be aiming directly at the head of every person present.

FIG. 265.—Illusion of lines always pointing toward observer.

In concluding this brief survey of some of the most important subjects connected with the physiology of vision it is well to utter a word of caution with regard to a danger connected with the study of the subject. This danger arises in part from the fact that in the scientific study of vision it is often necessary to use the eyes in a way quite different from that in which they are habitually employed, and more likely, therefore, to cause nervous and muscular fatigue. We have seen that in any given position of the eye distinct definition is limited to an area which bears a very small proportion to the whole field of vision. Hence in order to obtain an accurate idea of the appearance of any large object our eyes must wander rapidly over its whole surface, and we use our eyes so instinctively and unconsciously in this way that, unless our attention is specially directed to the subject, we find it difficult to believe that the power of distinct vision is limited to such a small portion of the retina. In most of the experiments in physiological optics, however, this rapid change of direction of the axis of vision must be carefully avoided, and the eye-muscles held immovable in tonic contraction.

Our eyes, moreover, like most of our organs, serve us best when we do not pay too much attention to the mechanism by which their results are brought about. In the ordinary use of the eyes we are accustomed to neglect after-images, intraocular images, and all the other imperfections of our visual apparatus, and the usefulness of our eyes depends very much upon our ability thus to neglect their defects. Now, the habit of observing and examining these defects that is involved in the scientific study of the eye is found to interfere with our ability to disregard them. A student of the physiology of vision who devotes too much attention to the study of after-images, for instance, may render his eyes so sensitive to these phenomena that they become a decided obstacle to ordinary vision.